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J.-F. Mercure[1,2,3*], H. Pollitt[3,2], J. E. Viñuales[2], N. R. Edwards[2,4], P. B. Holden[4], U. Chewpreecha[3], P. Salas[2], I. Sognnaes[2], A. Lam[2,5] and F. Knobloch[1,2]

[1]Department of Environmental Science, Radboud University, Nijmegen, The Netherlands. [2]Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG), University of Cambridge, Cambridge, UK. [3]Cambridge Econometrics Ltd, Covent Garden, Cambridge, UK. [4]Environment, Earth and Ecosystems, The Open University, Milton Keynes, UK. [5]Department of Economics, Faculty of Social Sciences, University of Macao, Taipa, Macau. *e-mail: J.Mercure@science.ru.nl

Macroeconomic impact of stranded fossil-fuel assets
Supplementary notes, figures and tables online

J.-F. Mercure[1,2,3*], H. Pollitt[3,2], J. E. Viñuales[2], N. R. Edwards[2,4], P. B. Holden[4], U. Chewpreecha[3], P. Salas[2], I. Sognnaes[2], A. Lam[2,5] & F. Knobloch[1,2]

Suppl. Note 1 | Differences between E3ME-FTT-GENIE and other models

Since it is a simulation model, and because the economic model is demand-led based on Post-Keynesian theory, E3ME-FTT-GENIE produces results that contrast with those from other detailed sectoral IAMs applied to climate change issues[1,2]. This is due to the model's non-equilibrium formalism, which represents finance and money creation[3,4], while equilibrium models used in most of the climate change literature do not represent money or banking. Including money and banking is important, because the financial system generates booms and recessions, such as that which took place in 2008. In demand-led models, production is not determined directly by the quantity of production capital available, but by the demand for products, and thus capital and labour can become stranded in particular situations.

Although E3ME is a sectoral model consistent with Post-Keynesian theory, it does not feature a detailed stock-flow model of finance or a model of financial contagion. Such features would be useful but are not crucial for the present study, which focuses on sectoral impacts, not financial stability. Stock-flow consistent Post-Keynesian models connected to climate modules exist[5,6]; however, none to date have the sectoral detail required in the present study. Meanwhile, attempts are being made to add the financial sector to equilibrium models, notably with the model GEM-E3-FIT (see [3]).

In conventional equilibrium models, capital resources are equal to total saving year on year. If capital resources are used to fund low-carbon technology, this requires either higher savings or results in the same quantity of capital resources being taken away from other productive sectors of the economy; both of these automatically lead to the GDP losses associated with climate mitigation action. This leads economists to frame climate mitigation as a prisoner's dilemma involving free-riders. Conversely, in the same models, if a sector loses output due to economic change (e.g. the fossil-fuel sector), the capital from this sector becomes free and immediately re-allocated to other sectors instead of being lost, compensating GDP even though the affected countries suffer the shutdown of a sector, the loss of machinery and rises in unemployment. We argue that in reality, the capital is not re-used for other purposes, but instead it is written off. Therefore, we argue, the assumption of capital re-allocation in these models artificially reduces the distributional impacts of climate mitigation, a problem that has mostly escaped attention, while it exclusively leads to GDP loss when climate policy is adopted. Equilibrium models also often assume full employment of the working age population, which has a similar effect.

[1] Department of Environmental Science, Radboud University, PO Box 9010, 6500 GL Nijmegen, The Netherlands, Tel.: +31 24 36 53256, E-mail: J.Mercure@science.ru.nl

[2] Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG),
[2] Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG), University of Cambridge, The David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK.

[3] Cambridge Econometrics Ltd, Covent Garden, Cambridge, CB1 2HT, UK

[4] Environment, Earth and Ecosystems, The Open University, Milton Keynes, UK

[5] Department of Economics, Faculty of Social Sciences, Humanities and Social Science Building, University of Macao, E21, Avenida da Universidade, Taipa, Macao
* Corresponding author

In non-equilibrium models such as E3ME-FTT-GENIE, neither of these two equilibrium-enforced effects take place. This is due to the fact that investment decisions are not directly constrained by saving decisions, as the balance is accounted for by changes in aggregate debt (borrowing or debt repayment), consistent with modern accounts of the monetary and financial systems[7-9]. This implies that in E3ME-FTT-GENIE, while there is no free-rider problem that arises with climate mitigation (climate action can lead to increases in investment, GDP and employment, without prior rises in saving), distributional impacts across sectors and regions are more pronounced (capital and labour can be stranded), in comparison to models that do not represent money, finance or details of the labour market.

We acknowledge work that has been done in other models concerning joining up top-down macroeconomic modelling to bottom-up technology modelling. Notably, many models were improved in this respect in the 2006 project entitled 'Endogenous Technological Change And The Economics Of Atmospheric Stabilisation',[10] and in 2010, 'The Economics Of Low Stabilization'.[2] More recently, other model comparisons have been carried out[11-13]. While highly valuable, these representations are, however, not sufficiently sophisticated to generate the type of insights presented in this paper.

Differences between E3ME-FTT-GENIE and the IEA's World Energy Model

We compare E3ME-FTT results with those of the IEA 'World Energy Outlook' (WEO) featured in Figure 1 of the main text, attempting to explain the differences. The IEA uses its flagship 'World Energy Model' (WEM) to create WEO forecasts[14]. Two key differences between that and E3ME-FTT are important to mention: (1) WEM does not model S-shaped non-linear technology diffusion, but uses multinomial logits instead, implying a standard representative agent with complete information, and (2) WEM uses exogenous GDP growth assumptions, on which energy demand projections rely. Since numerical assumptions in WEM are not given by the IEA for us to compare against ours, we base our explanation of outcome differences on model structure. We note that the energy component of E3ME-FTT is based on the same IEA energy balances data.

Point (1) implies that WEM models technology diffusion solely based on cost considerations, and is thus analogous to a standard cost-optimisation model without behavioural information. For instance, in its sub-component Momo for road transport, the diffusion of light-duty vehicles by technology type is not non-linear (as in self-reinforcing S-shaped diffusion) but instead technology choice relies linearly on cost data. This implies that changes in the state of diffusion only happen when relative prices change: if relative technology costs do not change over time, an active evolving policy is necessary (e.g. an increasing carbon price). Thus without policy, no diffusion takes place by construction, while in FTT, on-going diffusion processes exist even without policy, which are accelerated by climate policy.

Point (2) implies that since its total production is fixed, sectoral production in WEM can only respond to price changes but not to demand changes, as demand for energy end-use services is modelled based on these exogenous GDP growth assumptions. However, price changes themselves will also be partly fixed by the resulting relatively rigid sectoral output. Therefore, energy demand changes originate almost exclusively from technological change, not from the economy. For instance, when the demand in WEM for fossil fuels declines, but intermediate demand for equipment and products for investment in the fossil-fuel and heavy industry sectors does not change, this artificially mitigates intermediate demand reductions for energy substantially, which would be observed if sectoral output was modelled endogenously. This is a substantial source of SFFA in the present work, as sectoral output is fully endogenous, providing a more complete representation of the sources of change in energy demand.

These two points result in energy demand projections in the WEO to be partly determined exogenously through fixed GDP assumptions, partly through insufficiently sophisticated representations of technology diffusion. Although it responds to climate policy through price signals, total energy demand growth in the WEO is independent from many important endogenous factors such that SFFA cannot be observed in WEM.

Suppl. Note 2 | Sensitivity analysis for the technological trajectory

Sensitivity analyses were carried out to test the stability and robustness of scenarios with substantial changes to key technology parameters. The exercise was carried out for power generation and road transport, which together contribute 41% of current fuel use. Results are shown in Suppl. Tables 3 and 4. The parameters chosen are those that we expect will generate the largest changes to SFFA values. Changes are in percent for costs, and in added percentage points for rates. The parameters tested for power generation are (i) the capital costs of renewables (REN, ±20%), (ii) learning rates (±5 percentage points) and (iii) industry discount rates (±5 percentage points). For transport, the parameters are (iv) the prices of electric vehicles (EV, ±20%), (v) non-pecuniary costs (±20%), (vi) learning rates (±5 percentage points), (vii) consumer discount rates (±10 percentage points) and (viii) the fuel efficiency of new fossil fuel vehicles (±20%). We report the resulting changes, in % change over the same scenario without variation (i.e. $(\Delta S_2 - \Delta S_1)/\Delta S_2$), on the shares of renewables, of photovoltaic (PV), of EVs, of advanced efficiency combustion vehicles including hybrids (ADV) and conventional fossil fuel vehicles (FF), as well as changes in the value of fossil fuel assets for each fuel type and global GDP, discounted by 10% and cumulated to 2050.

The justification for these variations is as follows: (i) 20% is the maximum systematic error on mean capital costs we consider possible at one STD (the model, with its distributed cost formulation, already considers that around 30-40% of non-systematic cost variations exist, depending on the technology). (ii) power sector learning rates used range between 1% and 17%,[15] with a mean of 6%; variations cannot be more than 5-6 percentage points. (iii) Real world power sector discount rates are usually between 5% and 10%, depending on institutions[16,17]; systematic variations cannot exceed 5 percentage points. (iv) 20% is the maximum systematic errors on mean capital costs we consider possible at one STD (the model assumes distributed prices with STDs of 50%-80% of the mean for cars; EVs have lower price variations of 30% due to a lower number of models available). (v) Variations on non-pecuniary costs are reflections of systematic error on vehicle costs, and thus the same argument as (iv) applies. (vi) learning rates used are between 1% and 10% with mean of 5%; variations cannot exceed 5 percentage points. (vii) the consumer discount rate is 15%. In the literature, they span from 5% to 40% depending on the study design and assumptions[18,19]; thus at most 10 percentage points variations are possible. (viii) We use manufacturer fuel economy values, which are based on a standard driving cycle, adjusted to match total IEA fuel use for road transport. The driving cycle may not accurately represent driver behaviour leading to underestimation of around 30% in fuel use. We consider at most 20% systematic error possible at 1 STD.

We do not carry out directly sensitivities on fossil-fuel prices for the reason that these are not exogenous but endogenous variables in the model (there are no fossil-fuel price assumptions in E3ME-FTT); instead, fossil-fuel prices uncertainties can be caused by other exogenous assumptions such as the assumed reserve to production ratios chosen by producer countries. The sell-out itself is a process that results from such choices. SI Fig. 6 shows the impact of changing these values by 50%; this leads to changes on fossil-fuel prices of the order of 1% (coal), 5% (oil) 50% (gas). Fossil-fuel price variations could be caused by other factors such as armed conflict and other unexpected supply bottlenecks; however, we make the explicit assumption that this does not happen for simplicity of interpretation. Policy sources of uncertainty on SFFA are covered by SI Table 2. Fossil fuel prices are reported in Suppl. Table 7.

We do not allow varying the availability of technologies in the FTT models, for the following reason. FTT technologies are all, without exception, currently sold in markets (as evidenced by our historical data). Changing their availability would represent questioning reality if we remove them, while substantially increasing their future uptake beyond what can be achieved by modelling policy violates our diffusion modelling premise.

We observe that changes in our sensitivity analysis are relatively small in all cases. While changes in the technological shares can be of up to 16% ('2°C' scenario) and 60% ('Technology Diffusion Trajectory'), this generates changes to fossil fuel asset values of at most 11%. In terms of technology shares, we observe that the ‘Technology Diffusion Trajectory’ scenario is more prone to change, for changes in technology parameters, than the ‘2°C’ scenario, and this is explained by the fact that policy constrains more strongly outcomes in the ‘2°C’ scenario.

The largest impacts on fossil fuel asset values observed take place with changes of industry discount rates in power generation, which prompts substitution between coal and gas (thus exchanging coal and gas SFFAs) and, since gas has a higher price per energy content, impacts on asset values do not cancel out. Non-pecuniary (perceived) costs also affect oil asset values, as well as the fuel efficiency of combustion vehicles.

We combine the impacts using a root mean square. The interpretation for this is that if the uncertainty over technological parameters corresponded to the variations introduced here were independent and normally distributed, the resulting error propagation would be calculated in this way. If all such variations took place simultaneously, at most 15% uncertainty would be generated on fossil fuel asset values for each scenario. Since uncertainty could take place in both scenarios simultaneously, and that we calculate SFFAs using differences, at most 21% uncertainty would be generated. Although we do not know the real uncertainty over these parameters, experience with data tells us that these variations are reasonable. We conclude that for the policy scenarios considered, uncertainty on asset values is less than 21%, and therefore these scenarios are robust against variations of technology parameters. To estimate the maximum and minimum plausible variations in SFFA under combined variations of input parameters we performed two additional runs, which we used to generate the uncertainty bounds of Figures 2-3 of the main text. To achieve this, we used all parameter variations that generate increases in SFFA under the assumptions in Suppl. Table 3 in one model run, and all parameter variations that lead to lower SFFA in another, which we used as upper and lower uncertainty bounds.

It must be noted that our model is a diffusion model. In other models, if the model design involves searching the configuration space for the lowest cost configurations, and points in modelled time are not strongly dependent on past values, small changes in capital costs, discount rates or learning rates can generate relatively large differences in optimal technology configuration. This can be interpreted as modelling agents with perfect information and infinite access to technology. This is not what we do, which explains the relatively modest sensitivities obtained.

Here, the starting diffusion trajectory is constrained by the trajectory observed in recent historical data. The data constrain what near future configurations can be, which thus cannot radically change even for relatively large changes in parameters. Diffusion has, by definition, strong path-dependence and momentum in time and, by 2035, outcomes cannot be radically different from the present.

Similarly, altering the set of available technologies does not make much difference in FTT, for the following reason. Altering the ‘menu’ involves introducing new technologies (as stated above, we do not consider removing FTT technologies), with small market shares. Hypothetical new technologies with small shares take longer than until 2035 to diffuse to any significant degree, even if they possessed extremely attractive features (e.g. low cost) or policy support, only due to diffusion dynamics (unless a substantial public procurement program was assumed). In other words, 2035 is most likely too early for any new technology not modelled in FTT to radically change the landscape. This is a well known feature of the diffusion process, which, due to path-dependence, is rigid and contingent on history. This is supported by a whole body of literature on technological transitions[20-24]. Thus, the range of technological developments that one can observe in a diffusion model is more restricted than in models with weaker path-dependence.

Suppl. Note 3 | Assumptions of fossil asset owner behaviour

The representation of fossil asset owner behaviour in the fossil resource depletion algorithm[25] comes in the form of a rate of depletion expressed as a production to reserve ratio (in y^{-1}, see Suppl. Figure 5 B), a parameter defined for each year in each fossil-fuel producing E3ME region (see below). Fossil commodity prices are taken as global, while production and consumption are assumed to interact within a global pool. In each cost range, production is proportional to the local depletion rate times the amount of reserves remaining in that range, and the sum across all cost ranges determines total production in each region, while global production is equal to global demand. The marginal cost that matches global supply to global demand is searched for through iteration of the equations at each E3ME-FTT time step.

Following the standard definition, reserves are fossil fuels in the ground considered economic to extract, while resources cover all known fossil-fuel deposits, thus not necessarily economic. Economic viability is largely determined by comparing extraction costs to commodity prices. In situations of increasing or constant demand, as reserves are gradually consumed, prompting commodity prices to increase, the model assumes that quantities of nearly competitive resources are re-classified as reserves; their extraction begins, and their marginal cost sets the price. When demand declines, it is possible that some high-cost reserves are taken out of production and re-classified as resources, allowing a downward commodity price movement. Reserves in each cost range are extracted at the same rate regionally defined. The starting rate is empirically defined based on historical data[25], representing a combination of asset owner choices and technical rates of extraction. If lower cost producers increase their quota, they force higher cost producers to reduce theirs. Thus, if producers in regions operating predominantly in low-cost ranges (e.g. OPEC) so desire, they can increase their production to reserve ratio to undercut producers with higher costs in order to grab market share, i.e. extract their reserves faster in relation to the rate at which the price allows them to re-classify resources as reserves, effectively selling out their low-cost reserves instead of speculating on future prices. This could happen if low-cost producers begin to expect that future sales may be limited, in contrast to their past behaviour in which they expected sales to last indefinitely and reserved part of their product to sell at higher future prices[26].

Here, in the 'non-sell-out' scenarios, we assume constant production to reserve ratios, using those determined in earlier work[25] (their inverse equates to 44, 62 and 122 years for oil, gas and coal). A particular set of deviations of these parameters is what we call 'sell-out' scenarios, where we assume increasing ratios for low-cost producer countries (in particular Saudi Arabia and other OPEC countries), as shown in Suppl. Figure 5B. The particular values used were chosen such that production concentrates substantially towards OPEC (we assume that this is the purpose of decisions made in OPEC countries in order not to decrease their fossil-fuel income); a wide range of such values leads to similar outcomes, as shown in Suppl. Fig 6; reducing by 50% our chosen deviations in production to reserve ratios in all countries impact total cumulated SFFA and GDP by 8% (oil), <0.1% (coal), 29% (gas), 14% (total) and 15% (GDP).

Suppl. Note 4 | Contrasting wealth loss and output loss

Wealth losses (stocks of value of assets on firms' or individuals' balance sheets) are not the same as output losses (flows of value added, e.g. GDP loss). When a bubble bursts, assets suddenly lose their value. These losses appear on the balance sheets of firms, but do not necessarily imply loss of output for the economy. However, a common reaction of financial institutions is to substantially cut lending when they face substantially altered balance sheets[9,27]. This restricts investment, which leads to output loss in the real economy, in comparison to a scenario where banks continue lending. The cumulative impact of the latter effect can be much larger than the initial wealth loss, as was observed during the 2008 subprime mortgage crisis, since constraints on lending are likely to spill over to activities outside the sector in which the crisis originated[27].

Meanwhile, output loss can take place without any such financial effects, simply due to structural change in the economy, such as with the fossil-fuel extraction sector shutting down due to insufficient demand.

We distinguish two effects here: (1) disruptions to the finance of other non-fossil-fuel related activities (the fossil-fuel bubble bursting), caused by panic on financial markets resulting from the impact of a sudden loss of fossil-fuel wealth on balance sheets, and (2) the real economy impacts of significantly down-sizing the fossil-fuel sector.

In (1), losses to output due to restrictions of lending by financial institutions could be large or small, depending on whether the bubble is deflated calmly (early diversification of investment) or bursts suddenly, and whether warnings are heeded and investment in fossil-fuel assets is avoided as much as possible. A sudden burst could lead to worldwide loss of output outside the fossil-fuel sector, as happened recently with the financial crisis. *We do not quantify this effect in this study* because there is no widely accepted way to quantitatively predict these phenomena at this scale, as the true dynamics of these financial contagion effects at the global scale are not fully known.

In (2), structural change leads to loss of output in fossil-fuel producer countries and gains to fossil-fuel importer countries, with worldwide changes in GDP that roughly cancel out to below 1% change (i.e. distributional effects). *These effects are included since they can be modelled in detail in E3ME-FTT*. A dramatic bubble burst (1) would aggravate (2) into a financial crisis and recession. The consequence is that our projections of the degree of loss represent a minimum, which could be intensified, depending on the degree of financial disruption and the pace of financial contagion.

Wealth losses for different scenarios and investment horizons

Wealth losses in scenarios of stranded fossil-fuel assets originate from the process of investments being made based on expectations of higher returns than turn out to occur subsequently. Here, we consider various scenarios combining different asset owner behaviour and decarbonisation policy. The results are given in Suppl. Table 2, which shows, as rows, the scenarios expected by investors, and as columns, the scenarios that turn out to be realised. These values are consistent with recent exposure estimates[28] (see below), the latter now starting to be taken into consideration by banks in their decisions[29].

The interpretation is as follows. We take a scenario in which we assume an investment horizon year of 2035, and assume that investment is made in the present or near future, expecting return until the horizon date, based on subjective price projections by investors. We assume that investment costs are sunk, and return depends on whether the ventures turn out to be profitable. If the price and quantity sold turn out different than the projection, the wealth loss is the expected demand times the expected price minus the realised demand times the realised price over the simulation time span until the horizon year. Assets changing hands between the present and the horizon year make little difference to the outcomes; once someone has invested in fossil-fuel capital (e.g. pipelines, tankers, oil extraction equipment, drilling), subsequently selling the venture does not change the total value of the loss (although it may change who makes the loss). The key assumption is that the quantity of fossil-fuel assets expected to be burned is locked in once bets are placed and, if demand turns out less than committed supply, assets become stranded and the value invested is lost.

For example, we assume that investors take 2035 as a horizon and invest all capital needed for fossil-fuel production up to this date in the present, expecting returns based on demand and prices given in IEA projections[30]. They subsequently find, over later years, that the Paris Agreement is becoming fully implemented worldwide, that OPEC countries refuse to reduce their production substantially, and that therefore prices and demand are significantly lower than expected when investment decisions were initially made. Resources initially invested in extraction equipment (e.g. Arctic, deep offshore, tar sands) is lost since the assets expected to be extracted from the ground will never be burned (and new pipelines, tankers etc are never used). Companies may go bankrupt if their cashflows decline significantly, as they may default on bank loans, even if their production continues and is sold at low prices.

Different investment horizons yield different results, but do not generate additional insights. Instead, one may wish to consider SFFA values discounted at different rates (Suppl. Table 2) to represent the investment horizon on the basis that investors take bets on expected future discounted income. Since knowing what investors think is not possible, we provide a number of possible investor expectation scenarios, against the same set of realised scenarios, in matrix form. For example, if one considers that the selling-out by OPEC members is already committed and taken into account by investors, one may assume the 'IEA expectations' or 'Technology Diffusion Trajectory' scenario with sell-out, and contrast it against a '2°C' sell-out scenario, and observe the SFFA losses that arise then. In most scenarios, SFFA losses are comparable or larger than the initial 2007-8 sub-prime mortgage crisis loss[27]. The magnitude and direction of cumulated global GDP loss is highly dependent on the way remaining fossil-fuel production is distributed across the globe.

Our results are consistent, in a loose sense, with recent estimates of financial exposure for the EU and the USA. Battiston et al.[28] estimate around $1.7tn of value at risk when considering the fossil-fuel sector only. In our work, for the EU and the USA combined, we obtain $1.2tn (discounted) and $3.3tn (undiscounted) of total SFFA. The comparison can only be made loosely, since the values do not have the exact same meaning; while we calculate loss of income on sales of fossil fuels, Battiston et al. calculate the sum of the value at risk of assets of listed companies (loans, equity, etc). We do not know what investors expect as return, while the asset value plus return should in many cases be higher than the values they report. Nevertheless, we consider our values to be in the correct range, when considering their results.

Our results, however, are not quite consistent with Dietz et al.[31] Since the methodology and interpretation of the results differ substantially, they should not be compared. Dietz et al. use exogenous GDP growth as a proxy for climate Value at Risk, using Nordhaus' model DICE[32], and no real representation of the energy system, but they include climate damages as a probability distribution. In DICE, GDP decreases by assumption proportionally to abatement measures and damages[32]. In this formulation, investment devoted to abatement is by definition unproductive, and impacts on GDP of stringent climate policy can, by construction, only be negative (see the 'crowding out' issue discussed above). In contrast, while E3ME does not include climate damages, and therefore has no representation of 'fat-tailed' extreme events distributions, it provides a detailed sectoral account of abatement, investment, trade, and the impacts of these on output (for instance, positive employment impacts of building and deploying renewables). Since the quantity of money is endogenous, resources invested in mitigation do not require cancelling out resources invested in other parts of the economy (i.e. aggregate debt growth can increase GDP). Therefore, the overall impact on GDP of stringent climate policy can be positive in some countries and negative in others, by substantial amounts that in the case described here, cancel out to less than 1% in aggregate. To some degree, our results are driven by changes in trade, such that some regions' losses come alongside other regions' gains (as total exports equals total imports globally). The analyses are thus not really comparable.

Suppl. Note 5 | Impacts of investment and fossil-fuel prices on the macroeconomy

Fossil energy commodities are accounted for in E3ME's national accounting system, while energy prices are updated every year as they change. Declines in exports for producing regions lead in the model to reduced activity in the oil and gas or mining sectors and other sectors in their supply chains (through input-output tables), which can generate unemployment, and generally reduce regional GDP. Changes in fossil-fuel or electricity prices influence competitiveness but also investment in every sector, particularly energy intensive ones. Sectoral and regional details are given in Suppl. Table 8. More detailed data can be forwarded by the authors on request.

Selling carbon permits/allowances can generate significant income for the public sector. We take the assumption that this income is re-used by government for reducing income taxes. This contributes significantly to boosting industrial competitiveness. Governments cannot indefinitely accumulate this income, and thus will eventually spend it by funding new programmes. Changing the way in which it is spent does not change the results significantly[33]. It is possible, however, that some governments use this income to reduce deficits or repay debt; we assume here that this doesn't happen, as this subject is outside of the scope of our study. In our model, this would lead to a reduction of GDP that is independent from the effects presented here.

E3ME is demand-led, and therefore resources invested in one project do not require cancelling out resources invested in other parts of the macro-economy, as is the case in other models[3]. Thus investment-intensive scenarios tend to increase GDP and employment in the short term as activity grows in construction and other sectors related through input-output tables. This explains the emergence of growth related to building low-carbon infrastructure and equipment. The response of governments to falling economic activity due to loss of fossil fuel production would, in many cases, most likely involve deficit spending to mitigate large impacts on GDP and employment, notably in the USA and Canada. Here, we assume balanced government budgets instead and thus do not allow for this possibility, for clarity of the paper. In short, we do not allow changes in public debt, but we do allow changes in private debt.

Regional macroeconomic losses do not strongly depend on where fossil-fuel industry headquarters or shareholders are situated (often in Europe, e.g. Shell and BP), but rather, on where the activities of these companies take place (the Middle-East, Africa, Canada, etc), since this is where most of the investment takes place. Wealth losses by fossil-fuel firms and price falls affect their ability to (1) retain profit and (2) leverage banking and equity finance, both of which affect their ability to invest in new projects. These effects could have financial implications sensitive to the location of firms' headquarters but, as discussed above, we do not model losses in wealth (and their impacts on leveraging ability) but concentrate on losses in output. When new projects are cancelled, it is predominantly at the extraction location that the loss of employment and wage spending takes place and therefore here we neglect effects related to the geographical location of shareholders and firm headquarters.

Modelling fossil fuel markets and trade

Following the broader structure of the E3ME model, trade in fossil fuels is modelled using a demand-driven approach. First, econometrically estimated regional final demand is aggregated to the global level, and then the necessary global supply to meet this demand is allocated across regions according to their production costs, following the dynamics of our fossil-fuel supply model, where the marginal cost that matches global supply is sought, generating endogenous prices. We do not estimate trade on a bilateral basis (as we do for other products) since fossil fuels are commoditised products which violates the Armington assumption of differentiated production that underpins the modelling of trade in other sectors.[34] It is instead assumed that the available supplies are matched to demands in an efficient manner with transportation costs minimised.

E3ME includes end-user fuel prices including taxes, and these values are updated to reflect changes in fossil-fuel marginal costs from the fossil-fuel supply model; however end-user prices are not used in the calculation of SFFA. Fossil-fuel commodity prices used in the calculation of SFFA are obtained by adjusting calculated marginal costs for 2016 to the 2016 oil price (obtained from Bloomberg), and this scaling factor is maintained for subsequent years.

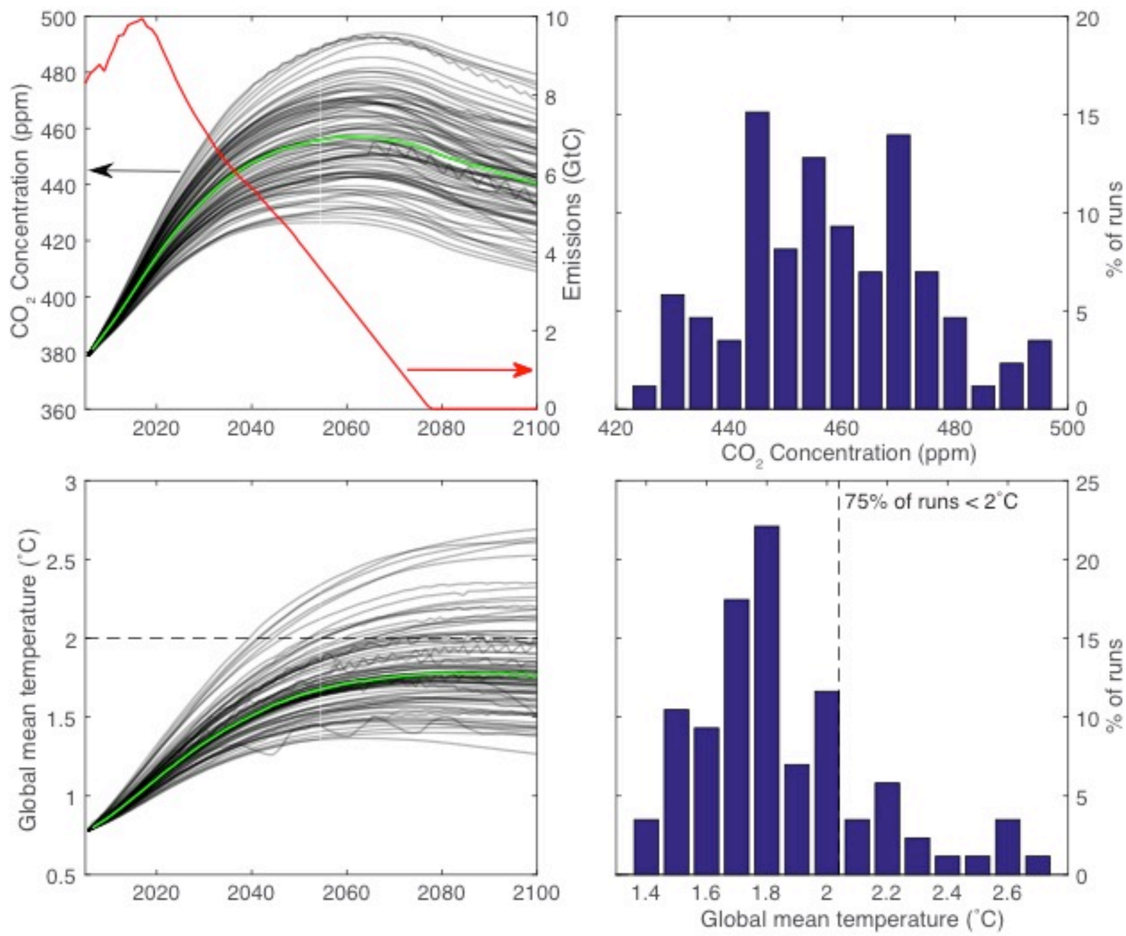
Sectoral economic impacts

Suppl. Table 8 provides sectoral and regional breakdowns of GDP and employment figures. The largest negative economic impacts occur in countries that are expensive producers of fossil fuels (e.g. Canada and the US). In these countries, even a small permanent drop in fuel prices can leave some fossil-fuel assets stranded, which has several important consequences for their national economies. First there is the direct effect of reduced production in the energy sector itself, with secondary effects from the loss of high-paid jobs and reductions in energy-sector investment activity. The loss of tax receipts (e.g. royalties) can be just as important, however, as these revenues are often used to fund public services and social programmes. The modelling assumes that government budgets are balanced so a loss of tax receipts implies a reduction in spending. Countries such as Canada therefore see reduced fuel exports, reductions in energy-sector investment, falling government expenditure and multiplier-based effects on household expenditure.

Supplementary Figures and Tables

Suppl. Table 1 | Methods summary

Model	Data and key mechanisms			Refs
Fossil fuel module	Main algorithm	$\Delta n(C,t) = \nu\, n(C,t) f(P-C)$, C =cost, Find price P such that $\int \Delta \mathrm{n}(\mathrm{C},\mathrm{t})\mathrm{dC} = Demand(P)$	$n(C,t)$ = cost distribution ν = production to reserve ratio	[25]
	Data sources	WEC, BGR, IEA, ETSAP, BP and other reports		[25,35]
FTT	Main algorithm	Diffusion: $\Delta S_i = \sum_j S_i S_j \left[A_{ij} F_{ij} - A_{ji} F_{ji}\right] \Delta t$, Binary logit: $F_{ij} = \left[1 + \exp\left(\frac{C_i + \gamma_i - C_j - \gamma_j}{\sigma_{ij}}\right)\right]^{-1}$,	S_i = Market share of option i A_{ij} = Building and turnover rates σ_{ij} = Agent heterogeneity γ_i = Non-pecuniary costs	[36-40]
	Data sources	FTT:Power: FTT:Transport: FTT:Heat:	IEA Energy Balances, IEA technology costs Eurostat, manufacturer websites, Marklines ODYSSEE, IEA, Agencies, academic papers	[16,17] [41] [37,42]
E3ME	Main algorithm	Linear co-integration econometric equations, with error-correction method [1] Demand = f(income, prices, interest rates, inflation, pop. age structure) [2] Investment = f(output, prices, wages, interest rates, spare capacity) [3] Bilateral trade = f(prices, tech. progress) [4] Prices = f(costs, import prices, tech. progress) [5] Employment = f(output, wages, tech. progress, working hours) [6] Prod. capacity = f(expected growth, tech. progress, population) [7] Energy demand = f(output, prices, investment, R&D)		[43] [4,33, 44-48]
	Data sources	Eurostat, OECD, Prodcom, World Bank, IEA, National statistics offices		
GENIE	Main algorithm	Atmospheric temperature field: 2D Energy-moisture balance dependent on net radiative forcing $R(t)$ $T_A(x,t) = f_1(T_O(x,t), I(x,t), C_A(t), C_L(x,t), R(t))$,		[49]
		Ocean temperature field: 3D Frictional-geostrophic ocean $T_O(x,t) = f_2(T_A(x,t), I(x,t), R(t))$,		[49]
		Atmospheric carbon timeseries, depends on emissions timeseries $E(t)$ $C_A(t) = f_3(T_O(x,t), I(x,t), C_O(x,t), C_L(x,t), E(t))$,		[50]
		Land carbon cycle: ENTS, depends on land-use change time series $L(t)$ $C_L(x,t) = f_4(T_A(x,t), C_A(x,t), L(t))$,		[51,52]
		Ocean carbon cycle: BIOGEM $C_O(x,t) = f_5(T_O(x,t), I(x,t), C_A(x,t))$,		[50,53]
		Sea-ice state $I(x,t) = f_6(T_O(x,t), T_A(x,t))$.		[49]
	Data sources	Data - validation against CMIP5 modelling output (see Suppl. Table 6)		

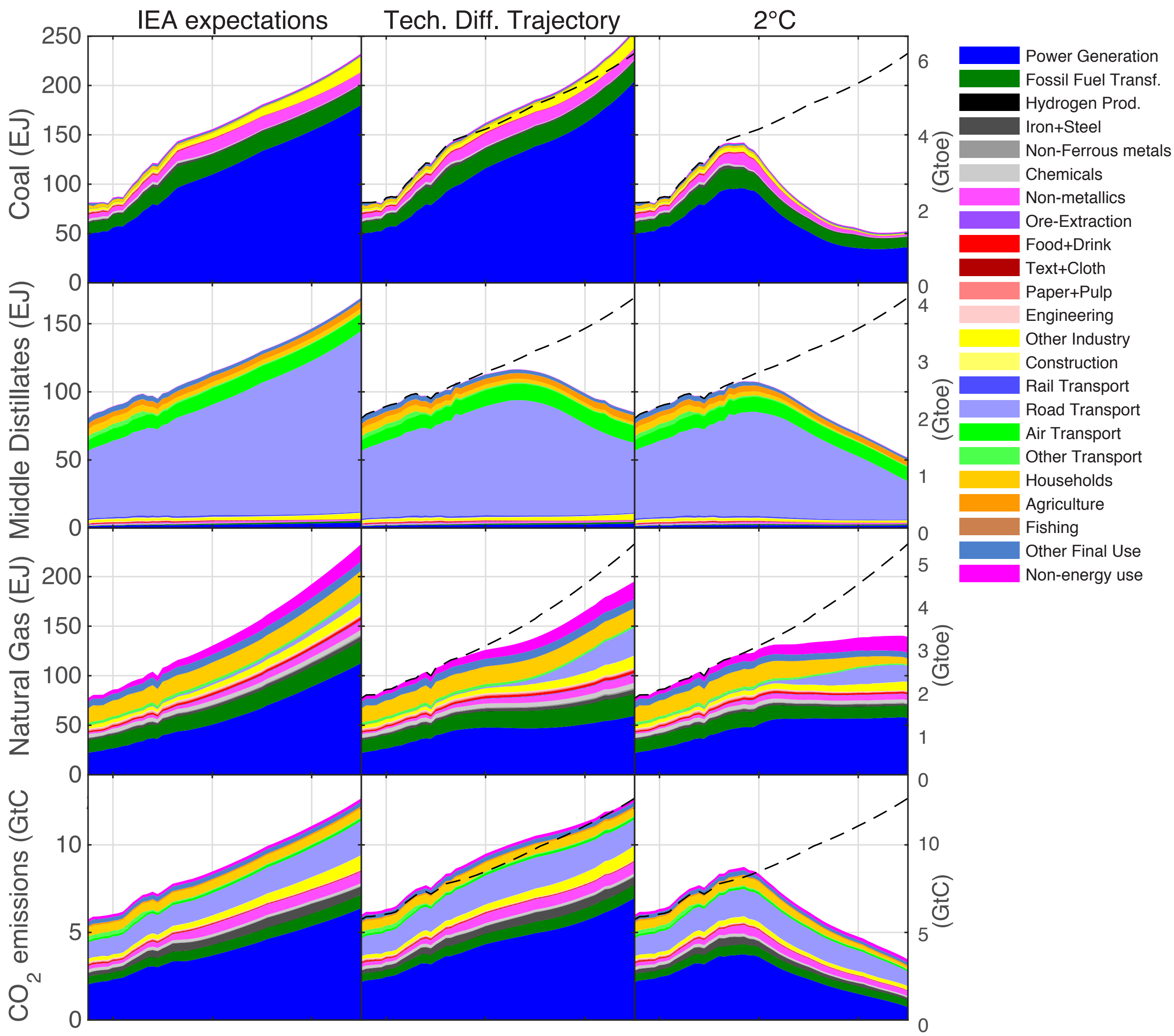


Suppl. Figure 1 | Climate impacts of the 2°C policies scenario. Concentrations (top panels). Global average temperature change (bottom panels). The bottom row shows model variations indicating 75% probability of not exceeding 2°C. Green lines indicate ensemble medians.

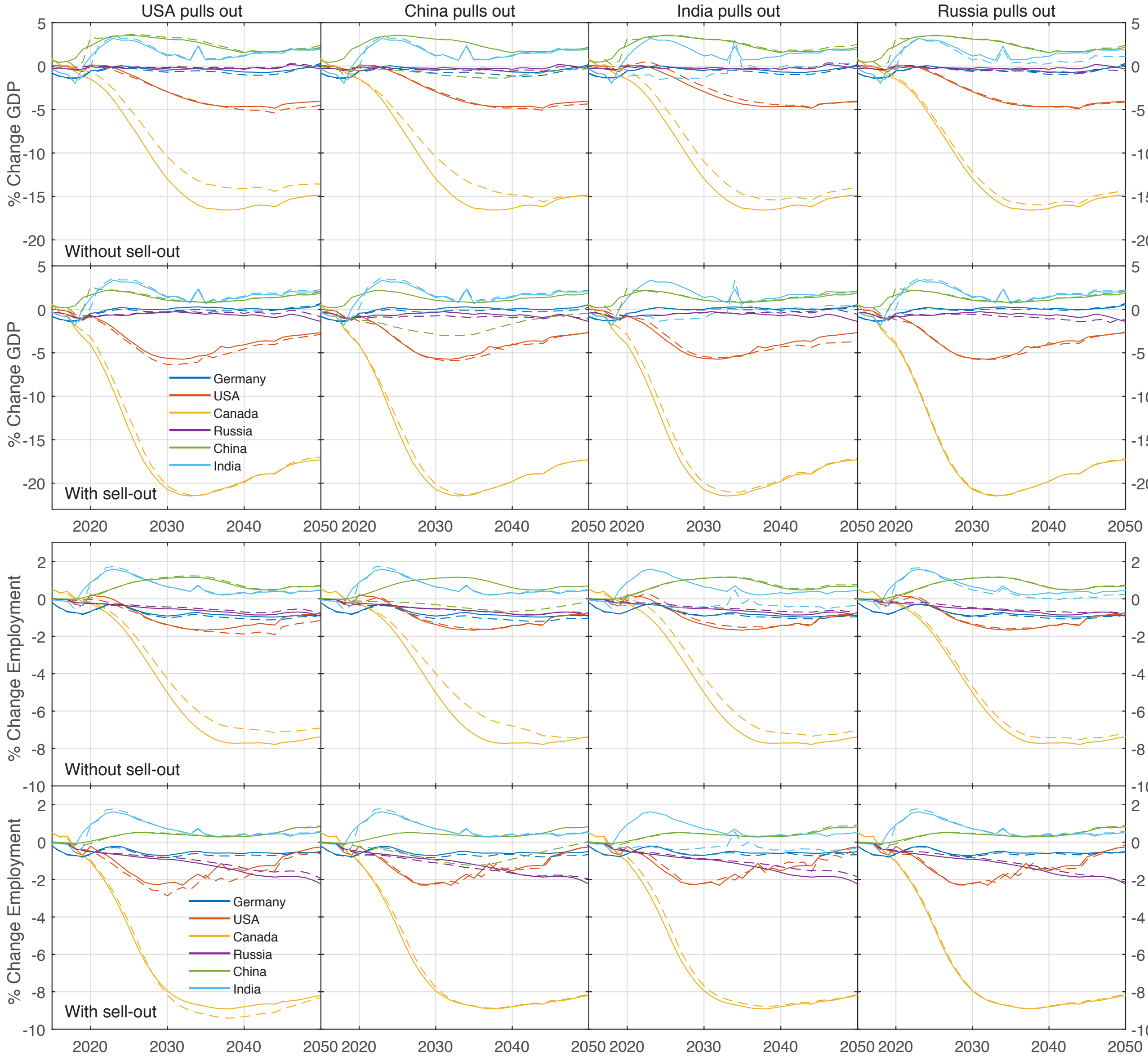
Suppl. Table 2 | Possible 2035 cumulative global total values of stranded fossil-fuel assets by fuel type and GDP changes, in trillions of 2016 USD ($tn), for relevant pairs of scenarios.

		IEA Sell-out			TDT			TDT Sell-out			2°C			2°C Sell-out		
		0%	5%	10%	0%	5%	10%	0%	5%	10%	0%	5%	10%	0%	5%	10%
IEA	Coal	0.0	0.0	0.0	-0.1	-0.1	0.0	-0.1	-0.1	0.0	1.0	0.6	0.3	1.0	0.6	0.3
	Oil	2.2	1.3	0.8	1.4	0.7	0.4	3.3	1.8	1.1	5.7	3.1	1.8	8.2	4.5	2.7
	Gas	1.5	0.9	0.5	1.4	0.8	0.5	2.8	1.6	1.0	1.6	0.9	0.5	3.2	1.8	1.1
	Tot	3.7	2.2	1.4	2.7	1.5	0.8	5.9	3.3	2.0	8.3	4.5	2.7	12.4	6.9	4.1
	GDP	24	13	7.7	-13	-8.3	-5.9	6.8	2.4	0.4	-17	-11	-8.3	-7.8	-6.0	-4.8
IEA Sell-out	Coal				-0.1	-0.1	0.0	-0.1	-0.1	-0.1	0.9	0.5	0.3	0.9	0.5	0.3
	Oil				-0.8	-0.6	-0.5	1.1	0.5	0.2	3.6	1.8	1.0	6.0	3.3	1.9
	Gas				-0.1	-0.1	0.0	1.2	0.7	0.4	0.1	0.0	0.0	1.7	0.9	0.5
	Tot				-1.0	-0.7	-0.6	2.2	1.1	0.6	4.6	2.4	1.3	8.7	4.7	2.7
	GDP				-37	-21	-14	-17	-11	-7.3	-41	-25	-16.0	-32	-19	-13
TDT	Coal							0.0	0.0	0.0	1.0	0.6	0.4	1.0	0.6	0.4
	Oil							1.9	1.1	0.7	4.4	2.4	1.5	6.8	3.8	2.3
	Gas							1.3	0.8	0.5	0.2	0.1	0.0	1.8	1.0	0.6
	Tot							3.2	1.9	1.2	5.6	3.1	1.8	9.7	5.4	3.3
	GDP							20	11	6.2	-3.9	-3.1	-2.4	5.0	2.3	1.1
TDT Sell-out	Coal										1.1	0.6	0.4	1.1	0.6	0.4
	Oil										2.5	1.3	0.8	4.9	2.7	1.6
	Gas										-1.2	-0.7	-0.5	0.5	0.2	0.1
	Tot										2.4	1.2	0.7	6.5	3.6	2.1
	GDP										-24	-14	-8.6	-15	-8.3	-5.1
2°C	Coal													0.0	0.0	0.0
	Oil													2.5	1.4	0.9
	Gas													1.6	0.9	0.6
	Tot													4.1	2.3	1.4
	GDP													8.9	5.4	3.5

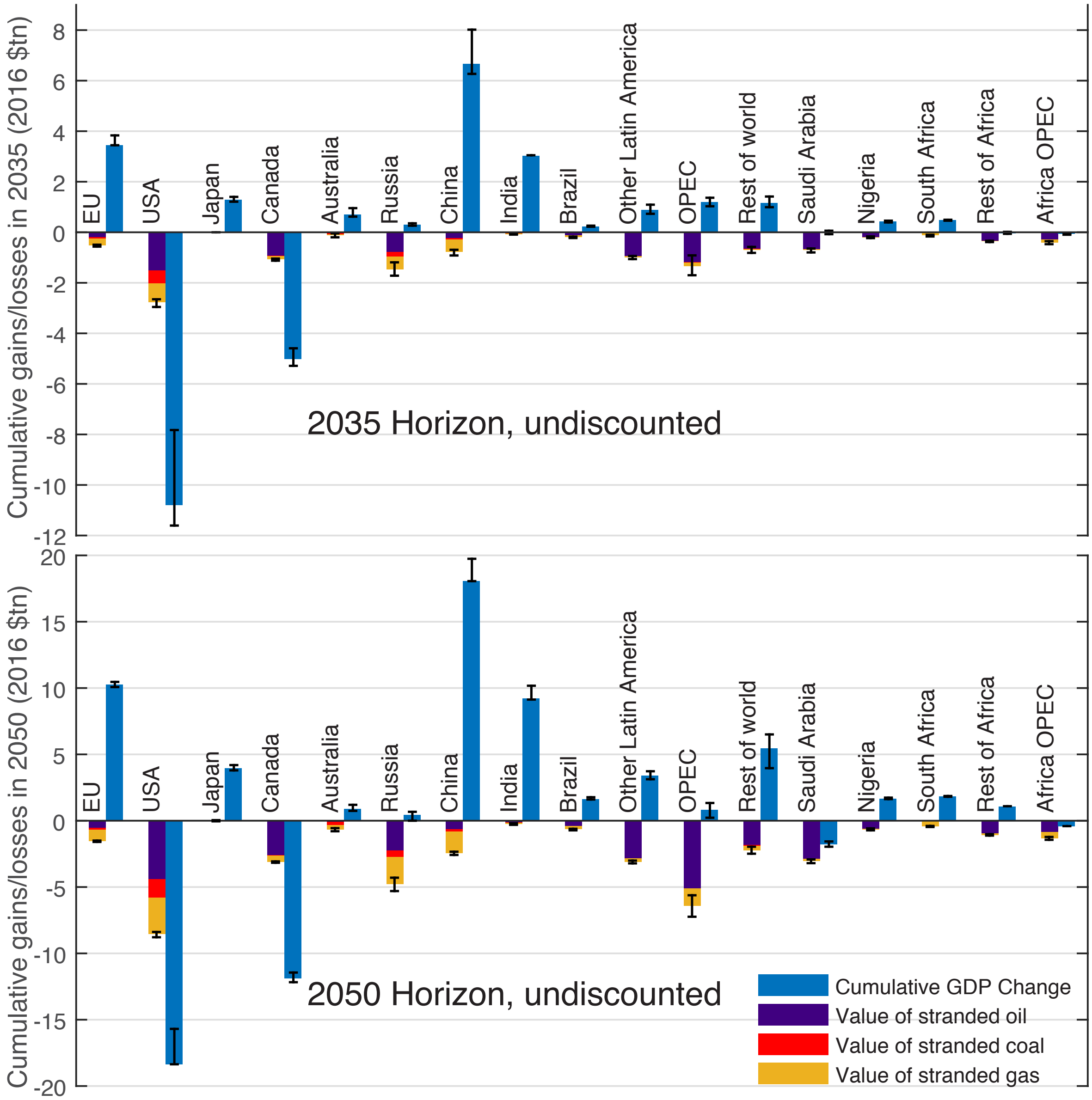
Notes: Numbers relate to loss incurred due to investors investing based on expectations of one scenario (rows) and facing another in reality afterwards (columns). Negative values refer to gains. Values are cumulated between 2016 and 2035, expressed in constant 2016 USD discounted with 0% (undiscounted), 5% and 10% rates. TDT refers to the 'Technology Diffusion Trajectory' E3ME-FTT scenario, IEA to the 'IEA expectations' scenario, while 2°C refers to our '2°C' scenario, based on E3ME-FTT, that achieves emissions reductions consistent with 75% probability of not exceeding 2°C of global warming. Colouring is a guide to the eye to indicate scenarios that have highest amounts of stranded assets (in red). The black boxes identify the three carbon bubble scenarios discussed in the main text.



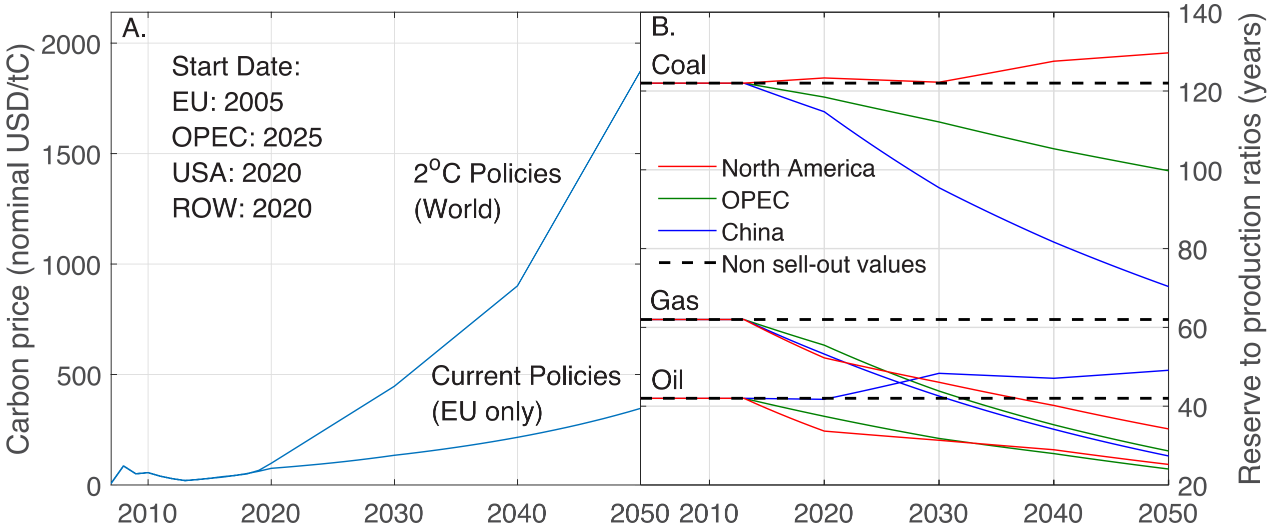
Suppl. Figure 2 | Global demand for fossil fuels. Coal, middle distillates (petrol and diesel) and natural gas by E3ME fuel user, followed by global fuel combustion and industrial emissions. These are given for a baseline involving fuel demand from the IEA (9) (first column), fuel demand fully endogenously determined by E3ME-FTT under the 'Technology Diffusion Trajectory' (second column), and an E3ME-FTT scenario with global emissions consistent with a 75% chance of not exceeding 2°C of warming (third column). Dashed lines refer to the 'IEA expectations' scenario for comparison.



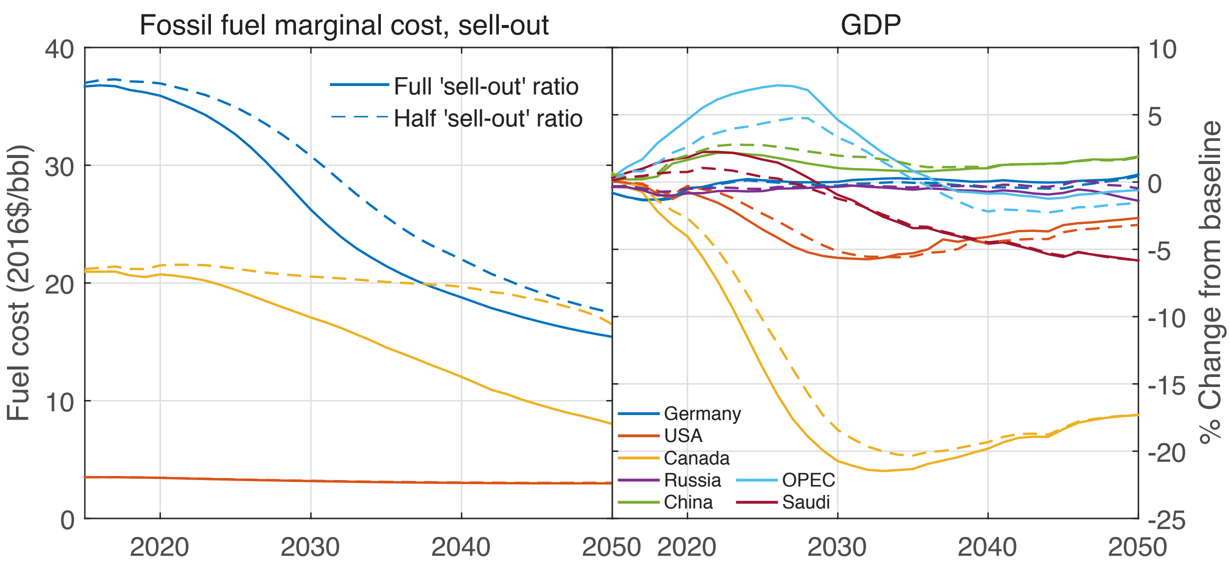
Suppl. Figure 3 | Macroeconomic impacts of regional withdrawals from the Paris Agreement. GDP (top 8 panels) and employment (bottom 8 panels), for the normal non-sell-out case (top rows) and the sell-out case (bottom rows). The solid lines refer to the 2°C policies scenario compared to the Technology Diffusion Trajectory baseline with all countries respecting the Paris Agreement, while the dashed lines refer to equivalent withdrawal scenarios.



Suppl. Figure 4 | Cumulative gains/losses for different horizons. Undiscounted cumulated SFFA losses and changes in GDP up to 2035 (top) and 2050 (bottom) between the '2°C' sell-out scenario and the 'IEA expectations' scenario. Error bars represent maximum uncertainty generated by varying technology parameters (see SI Tables 3-4).



Suppl. Figure 5 | Carbon price and production/reserve assumptions. A) Carbon price assumptions for each scenario, in nominal terms (including inflation). In our 'Technology Diffusion Trajectory' scenario, the carbon price only applies to the EU. In the 'policies for '2°C' scenario, all countries adopt a form of carbon pricing or taxing. A single price globally was used with different implementation dates indicated. In real terms, this carbon price means different values in different regions (due to different inflation rates), of the order of 200USD/tCO_2. B) Assumptions for the selling-out behaviour of fossil-fuel producers, expressed in reserve to production ratios (i.e. years left of reserves at current production), without sell-out (dashed lines) and with sell-out (coloured lines), chosen as values that lead to production concentration in the Middle-East (other countries not shown). Here, OPEC includes Saudi Arabia.



Suppl. Figure 6 | Effect of production to reserve ratio. A) Sensitivity test on fuel prices by halving the value of the deviation of the sell-out production to reserve ratio parameter given in Fig S5 B (dashed lines) in comparison to the 'policies for 2°C' sell-out scenario. B) Impact on GDP in this sensitivity test. OPEC excludes Saudi Arabia for higher detail. Impacts on total cumulated SFFA and GDP values are of less than 15%.

Suppl. Table 3 | Sensitivity analysis on technology parameters.

	Sensitivity parameters		% Change technology shares					% Change discounted SFFA & GDP				
	FTT Baseline	Var	REN	PV	EV	ADV	FF	Oil	Gas	Coal	Tot	GDP
Power Generation	REN capital costs	+20%	-7.85	-15.5	0.00	0.00	0.00	-0.04	0.21	1.87	0.15	-0.01
	REN capital costs	-20%	6.90	9.16	0.00	0.00	0.00	0.04	-0.04	-1.95	-0.11	0.01
	REN learning	+5pp	5.44	16.8	0.00	0.00	0.00	0.03	0.01	-0.85	-0.03	0.00
	REN learning	-5pp	-6.47	-27.1	0.00	0.00	0.00	-0.05	0.05	0.79	0.03	-0.01
	Discount rate	+5pp	-2.86	58.7	0.00	0.00	0.00	0.37	11.2	-3.80	3.22	0.38
	Discount rate	-5pp	14.3	-16.2	0.00	0.00	0.00	-0.12	-9.08	-0.11	-2.70	-0.19
Road Transport	Perceived costs	+20%	0.12	0.31	-5.47	0.66	1.11	2.24	-0.10	0.01	1.43	0.06
	Perceived costs	-20%	4.25	-13.0	-33.1	-2.94	18.5	-2.52	0.44	0.16	-1.50	0.44
	Learning rates	+5pp	-0.03	-0.10	3.49	3.53	-7.41	-0.90	0.63	0.04	-0.40	-0.01
	Learning rates	-5pp	-0.03	-0.15	-10.1	-2.93	9.10	1.13	-0.36	0.24	0.64	0.11
	Discount rate	+10pp	-0.02	0.00	6.94	0.04	-2.90	-0.80	0.10	0.01	-0.49	-0.01
	Discount rate	-10pp	0.06	0.16	-8.98	0.16	3.39	0.90	-0.09	0.00	0.55	0.02
	EV costs	+20%	-0.08	-0.59	-9.49	1.74	0.93	0.11	-0.03	-0.03	0.06	-0.01
	EV costs	-20%	0.04	0.55	8.44	-1.56	-0.80	-0.10	0.03	0.03	-0.05	0.01
	ADV Fuel Efficiency	+20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	ADV Fuel Efficiency	-20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Combined model run upper		-18.19	5.96	-20.92	-7.18	27.10	3.67	12.13	-0.49	5.74	0.54
	Combined model run lower		19.19	-10.34	0.09	11.48	-26.95	-3.20	-8.69	-1.49	-4.60	-0.29
	Root mean square		20.3	72.3	39.1	5.97	22.4	3.89	14.4	4.83	4.80	0.64
	2°C scenario	Var	REN	PV	EV	ADV	FF	Oil	Gas	Coal	Tot	GDP
Power Generation	REN capital costs	+20%	-0.07	4.88	0.00	0.00	0.00	0.00	1.41	-1.56	0.41	0.00
	REN capital costs	-20%	-0.06	-6.19	0.00	0.00	0.00	0.00	-1.29	1.81	-0.35	0.00
	REN learning	+5pp	0.18	-5.75	0.00	0.00	0.00	0.03	-0.89	1.57	-0.21	0.03
	REN learning	-5pp	-0.43	4.30	0.00	0.00	0.00	-0.02	0.76	-1.24	0.19	-0.02
	Discount rate	+5pp	-3.03	7.60	0.00	0.00	0.00	0.22	10.5	-6.38	3.35	0.22
	Discount rate	-5pp	3.84	-10.4	0.00	0.00	0.00	-0.02	-10.8	5.24	-3.36	-0.02
Road Transport	Perceived costs	+20%	0.01	-0.23	-2.35	1.07	9.30	1.91	0.26	-0.01	1.28	0.00
	Perceived costs	-20%	-0.27	-4.17	12.1	-8.00	-16.2	-3.21	0.05	0.04	-1.99	0.11
	Learning rates	+5pp	-0.01	0.10	1.37	-0.02	-6.71	0.08	0.02	0.00	0.06	0.00
	Learning rates	-5pp	-0.12	-0.19	4.53	-7.98	7.14	-0.36	-0.17	0.02	-0.28	0.01
	Discount rate	+10pp	-0.20	-0.23	12.9	-12.1	-3.75	-1.03	-0.21	0.04	-0.71	0.01
	Discount rate	-10pp	0.10	0.31	-11.8	9.89	5.34	1.07	0.18	-0.03	0.73	-0.01
	EV costs	+20%	0.02	0.05	-2.46	1.13	0.09	0.07	-0.02	0.00	0.00	0.00
	EV costs	-20%	-0.01	-0.03	2.85	-1.24	-0.14	-0.06	0.02	0.01	-0.03	0.00
	ADV Fuel Efficiency	+20%	-0.03	0.13	-0.59	0.41	-4.03	3.34	-0.06	-0.01	2.08	-0.03
	ADV Fuel Efficiency	-20%	0.03	-0.12	0.81	-0.52	5.43	-3.35	0.08	0.01	-2.08	0.03
	Combined in model run upper		-3.30	11.15	-12.55	8.12	18.78	2.78	12.91	-5.52	5.56	0.27
	Combined in model run lower		3.54	-16.73	11.67	-13.68	10.33	-1.34	-11.0	4.82	-4.08	-0.10
	Root mean square		6.39	26.9	22.3	19.4	23.1	6.73	15.2	13.9	6.33	0.25
	Scenarios combined		21.3	77.1	45.0	20.3	32.2	7.77	20.9	14.7	7.94	0.69

Abbreviations: REN = shares of renewables + nuclear, PV = shares of solar photovoltaic, EV = shares of electric vehicles, ADV = shares of future higher efficiency combustion vehicles, FF = shares of conventional combustion vehicles (in 2050). SFFA and GDP are discounted and cumulated to 2050. Note that 'pp' refers to percentage points. Combined model runs combine parameters above in single model runs with several variations, while root mean squares combine runs with individual variations.

Suppl. Table 4 | Uncertainty ranges for regional SFFA and GDP changes, in 2016bn$, based on the sensitivity analysis given in Suppl. Table 3, corresponding to error bars in Fig. 3 and Suppl. Fig. 4. Values in coloured boxes are SFFA values, numbers to the right are matching uncertainty ranges. Columns denoted with '+' and '-' refer to maxima and minima of uncertainty ranges.

2035 horizon, Discounted 10%

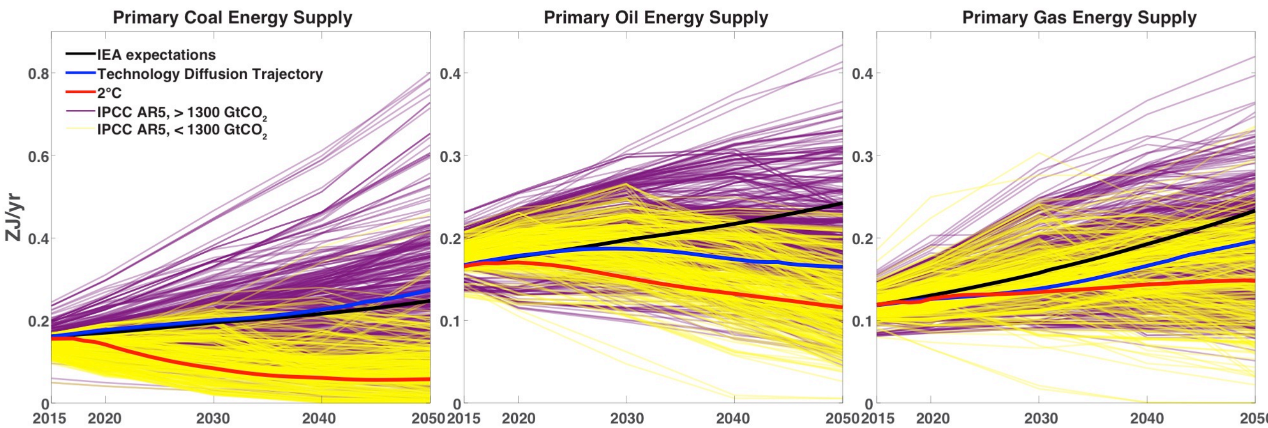
Country	Oil	Coal	Gas	Total	GDP	Oil +	Oil -	Coal+	Coal -	Gas +	Gas -	Total+	Total -	GDP +	GDP -
EU	68.2	19.3	103.5	190.9	-1368	1.6	-3.3	0.9	-0.7	15.4	-19.3	-15.9	20.5	22.4	-93.2
USA	525.7	186.6	250.5	962.7	3298	18.7	-34.6	15.6	-13.8	56.5	-83.2	-61.1	91.4	-1491	591.0
Japan	-0.1	0.1	-0.3	-0.3	-458.5	0.0	0.0	0.0	0.0	0.1	-0.1	-0.1	0.1	36.4	-45.9
Canada	324.6	5.2	47.0	376.8	1739.1	11.5	-20.8	0.4	-0.4	13.1	-18.0	-17.4	27.5	-208.7	144.8
Australia	-4.8	26.3	-9.2	12.2	-379.5	0.7	-1.6	5.1	-4.6	29.8	-37.9	-30.2	38.3	-116.9	54.3
Russia	276.1	66.3	178.6	521.0	-130.7	7.6	-16.2	7.1	-6.3	106.1	-94.2	-106.6	95.9	-20.2	5.7
China	81.4	18.9	167.1	267.4	-2987	2.1	-4.1	2.3	-2.0	40.1	-60.3	-40.2	60.5	-679.6	366.1
India	11.1	6.3	7.4	24.7	-1248	0.3	-0.7	0.7	-0.7	4.0	-4.4	-4.1	4.6	1.8	-25.5
Brazil	37.2	0.1	23.3	60.5	-103.9	2.0	-4.4	0.0	0.0	5.4	-8.3	-5.8	9.4	8.6	-10.6
LAM	327.6	0.2	16.4	344.2	-299.5	12.0	-24.0	0.1	-0.1	19.4	-18.4	-22.8	30.2	60.4	-83.8
OPEC	298.3	1.3	30.6	330.3	-577.3	27.0	-70.3	0.1	-0.1	148.4	-116.1	-150.8	135.7	-37.8	47.0
ROW	238.7	6.2	15.1	260.1	-328.5	6.2	-13.2	0.8	-0.7	45.4	-36.9	-45.8	39.2	-60.0	21.7
Saudi	172.3	0.0	6.3	178.7	-63.0	15.0	-38.8	0.0	0.0	17.0	-13.7	-22.6	41.2	-31.7	18.5
Nigeria	71.8	0.1	1.4	73.2	-136.3	1.9	-4.8	0.0	0.0	12.3	-9.6	-12.5	10.7	13.8	-14.4
S Africa	0.1	0.6	42.2	42.9	-177.3	0.0	0.0	0.1	-0.1	7.9	-13.2	-7.9	13.2	-3.2	2.5
R Africa	123.5	1.3	7.8	132.6	73.9	3.2	-6.9	0.2	-0.1	9.2	-8.2	-9.7	10.8	5.7	-27.1
A OPEC	101.3	0.0	45.0	146.3	19.2	2.7	-6.9	0.0	0.0	22.3	-24.5	-22.5	25.5	-1.6	0.1

2035 Horizon, Undiscounted

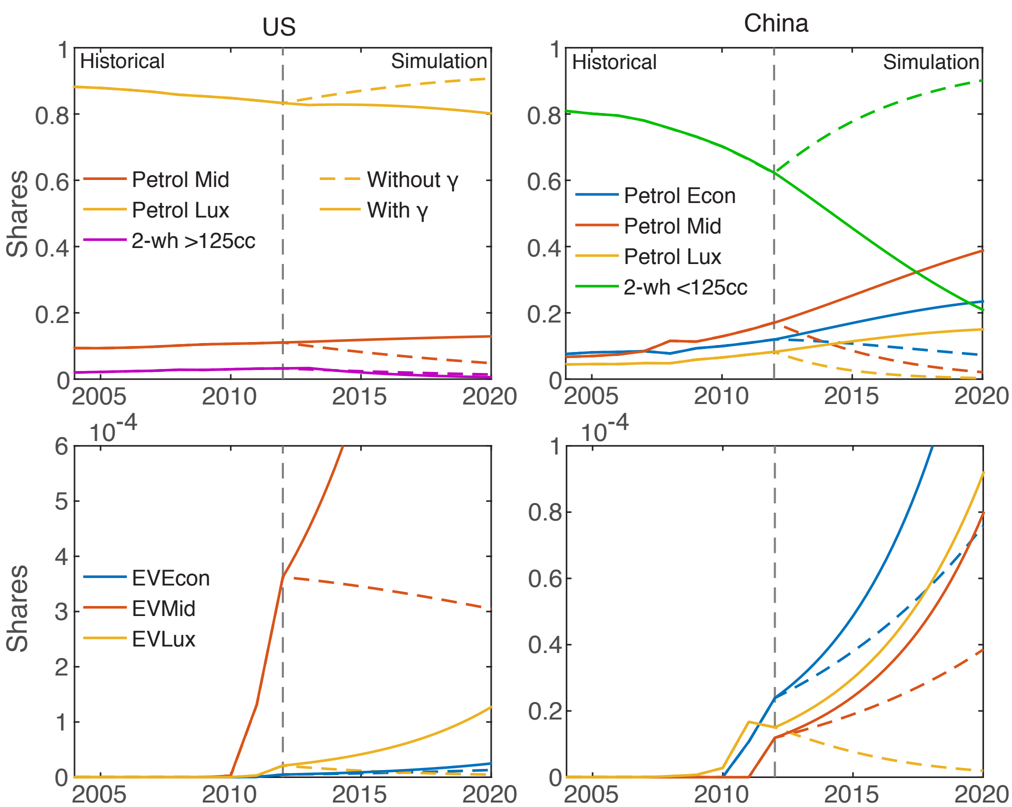
Country	Oil	Coal	Gas	Total	GDP	Oil +	Oil -	Coal+	Coal-	Gas +	Gas -	Total+	Total -	GDP +	GDP -
EU	191.1	50.4	284.4	525.9	-3448.4	2.4	-6.3	1.9	-1.8	32.6	-39.4	-33.3	41.5	3.9	-385.2
USA	1506.4	518.3	749.3	2774.0	10800	27.4	-58.0	36.1	-36.1	113.9	-169.1	-122.6	182.4	-2974	806.1
Japan	-0.1	0.4	-0.6	-0.3	-1285.5	0.0	0.0	0.1	-0.1	0.2	-0.2	-0.2	0.2	75.7	-115.2
Canada	918.7	14.4	140.6	1073.6	5016.3	16.9	-34.0	1.0	-1.0	27.0	-37.8	-31.9	50.8	-425.0	269.8
Australia	1.3	84.3	29.0	114.7	-705.9	1.1	-3.4	12.4	-12.7	67.4	-84.7	-68.6	85.7	-249.7	87.7
Russia	771.4	187.9	518.5	1477.8	-301.2	11.5	-32.9	16.8	-17.1	286.7	-237.6	-287.5	240.5	-53.1	39.8
China	227.7	54.2	489.5	771.3	-6668.4	3.1	-7.6	5.4	-5.5	77.8	-125.4	-78.0	125.7	-1350	400.3
India	33.1	17.9	23.1	74.1	-3020.3	0.5	-1.6	1.8	-1.8	10.0	-10.4	-10.1	10.6	25.5	-27.7
Brazil	116.2	0.3	68.2	184.7	-219.6	3.0	-9.4	0.1	-0.1	10.6	-17.2	-11.0	19.6	13.3	-37.6
LAM	940.7	0.7	56.5	997.8	-888.6	17.9	-44.8	0.2	-0.2	51.9	-46.0	-54.9	64.2	158.3	-202.9
OPEC	1185.2	3.7	153.2	1342.1	-1205.2	42.6	-170.5	0.3	-0.3	424.6	-315.3	-426.7	358.5	-161.0	176.3
ROW	649.5	17.7	43.9	711.1	-1155.7	9.3	-27.1	1.8	-1.9	131.2	-101.0	-131.5	104.6	-258.5	163.1
Saudi	672.1	0.0	25.6	697.7	30.8	23.6	-93.6	0.0	0.0	48.1	-36.6	-53.6	100.5	-91.7	44.8
Nigeria	198.4	0.2	4.0	202.6	-424.9	3.0	-11.1	0.0	0.0	36.2	-26.8	-36.3	29.0	35.5	-33.2
S Africa	0.3	1.8	121.2	123.4	-490.4	0.0	0.0	0.2	-0.2	14.4	-27.3	-14.4	27.3	-4.9	4.5
R Africa	336.2	3.6	22.7	362.5	46.3	4.9	-14.3	0.4	-0.4	25.7	-21.5	-26.2	25.8	12.3	-63.4
A OPEC	280.8	0.0	129.5	410.3	69.8	4.3	-16.3	0.0	0.0	56.4	-58.8	-56.5	61.0	-4.3	-0.6

2050 horizon, Undiscounted

Country	Oil	Coal	Gas	Total	GDP	Oil +	Oil -	Coal+	Coal-	Gas +	Gas -	Total+	Total -	GDP +	GDP -
EU	524.6	122.7	895.2	1542.5	-10275	3.0	-7.5	2.8	-3.0	42.7	-54.0	-43.7	56.1	201.0	-189.6
USA	4402.1	1375.0	2771.0	8548.1	18359	29.7	-62.3	58.4	-65.6	146.7	-220.1	-163.4	236.1	-2667	1252.5
Japan	0.3	1.1	-0.6	0.8	-3944.6	0.0	0.0	0.1	-0.1	0.4	-0.5	-0.5	0.5	150.9	-249.0
Canada	2580.0	38.2	489.7	3107.9	11897	17.3	-34.8	1.6	-1.8	35.1	-50.5	-39.2	61.3	-452.0	275.7
Australia	61.7	255.9	344.2	661.7	-893.1	1.7	-4.4	22.8	-26.4	97.7	-130.1	-101.2	132.1	-305.4	153.1
Russia	2217.7	511.1	2054.8	4783.7	-445.5	15.5	-40.4	29.4	-33.6	487.0	-517.1	-488.4	519.5	-226.4	300.8
China	640.7	148.3	1639.9	2428.9	-18060	3.8	-8.9	9.8	-11.3	91.4	-150.6	-92.2	151.2	-1683	244.9
India	96.9	49.1	92.5	238.6	-9210.9	0.7	-2.1	3.2	-3.8	16.0	-19.1	-16.5	19.5	77.3	-964.3
Brazil	386.4	1.0	234.6	621.9	-1607.4	4.7	-12.5	0.1	-0.1	12.8	-21.1	-13.7	24.5	7.1	-164.2
LAM	2812.3	2.3	285.8	3100.3	-3404.5	22.8	-53.5	0.3	-0.3	91.2	-101.3	-94.0	114.6	277.7	-323.4
OPEC	5094.9	9.9	1294.3	6399.1	-806.5	84.0	-245.2	0.5	-0.6	774.9	-802.7	-779.5	839.3	-529.5	581.4
ROW	1819.6	48.0	346.5	2214.0	-5455.4	13.2	-34.3	3.5	-4.1	252.8	-271.1	-253.2	273.3	-1049	1493.3
Saudi	2840.7	0.0	175.8	3016.5	1792.9	46.1	-134.1	0.0	0.0	87.2	-91.1	-98.7	162.1	-229.3	160.2
Nigeria	580.2	0.4	69.4	650.0	-1670.6	5.3	-15.4	0.0	0.0	70.6	-74.8	-70.8	76.4	42.6	-69.7
S Africa	0.9	4.9	400.9	406.7	-1838.4	0.0	0.0	0.3	-0.4	14.6	-29.2	-14.6	29.2	-25.4	31.7
R Africa	938.7	9.7	116.2	1064.6	-1048.6	6.9	-18.1	0.7	-0.8	48.3	-53.2	-48.8	56.2	43.5	-44.8
A OPEC	827.9	0.0	493.5	1321.4	408.6	7.8	-22.8	0.0	0.0	96.0	-115.9	-96.3	118.1	-6.1	0.2



Suppl. Figure 7 | Comparison with IPCC. This work's fossil energy supply displayed on top of the IPCC AR5 ensembles. Dark purple curves are scenarios of which cumulative emissions are greater than 1300 $GtCO_2$ (355 GtC), while yellow curves are below, where 1300 $GtCO_2$ is considered to approximately match 50% chance of remaining below 2°C.[54] Data obtained from the AR5 scenario database at tntcat.iiasa.ac.at/AR5DB/ .



Suppl. Figure 8 | Empirical determination of non-pecuniary costs. Comparison of FTT model outputs, taking private passenger transport as an example, to show the role of the γ factors representing non-pecuniary costs. Dashed lines are model outputs with $\gamma = 0$, solid lines are model outputs with γ factors minimising the difference in trajectory (slope difference) between historical data (left of the vertical dashed line) and the FTT simulation (right of the vertical dashed line). All technologies in every region were assessed visually by the authors. The γ factors are interpreted as all costs not explicitly specified in the FTT formulation. Lux, Mid and Econ refer to engine size or power vehicle class, EV stands for electric vehicles, 2-wh stands for two-wheelers[39]. Other vehicle types in the model are not shown for clarity of presentation.

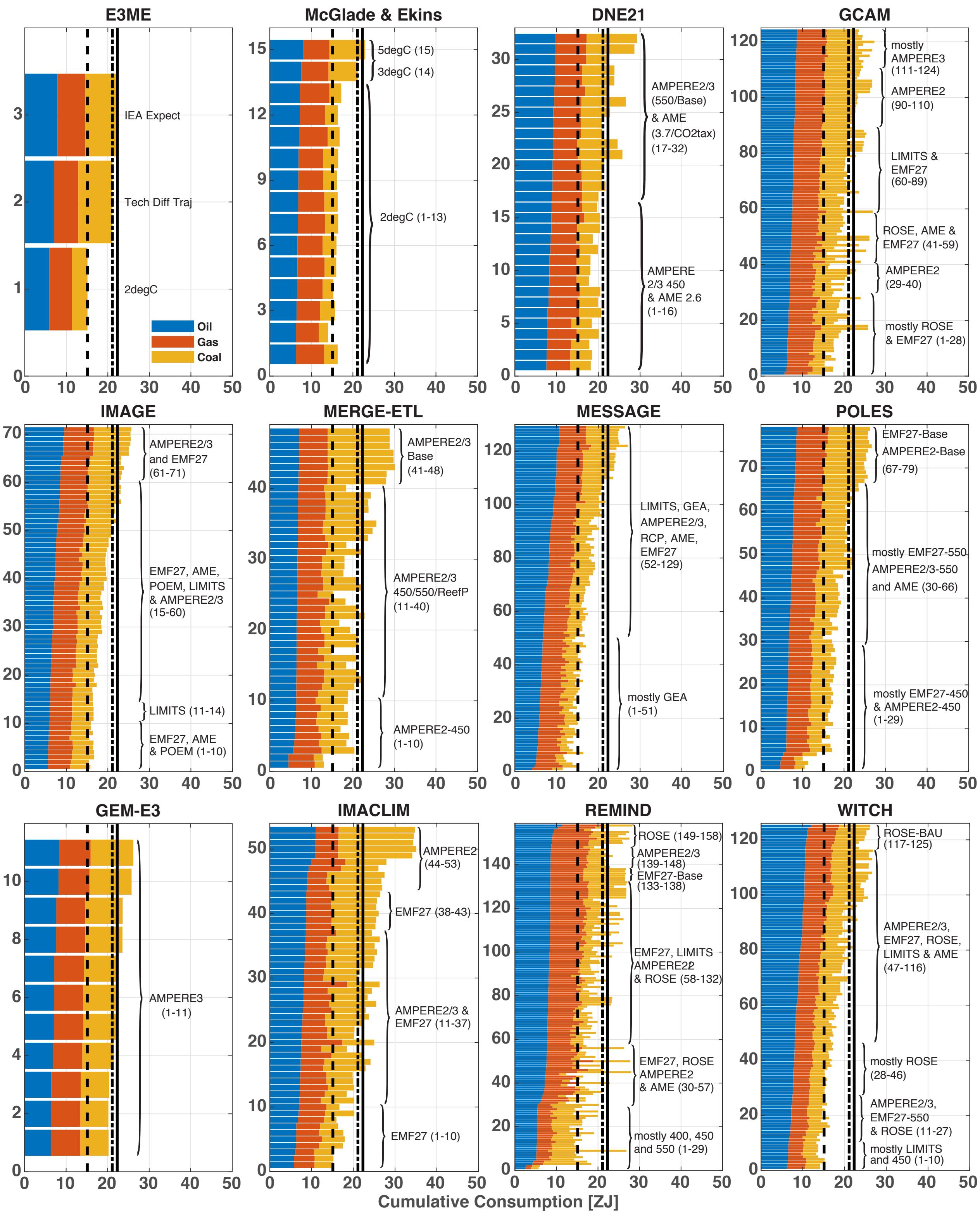
Suppl. Table 5 | Comparison of the main scenarios presented in this paper with other modelling exercises. Cumulative production of fossil fuels in the 'IEA expectations', 'Technology Diffusion Trajectory' and '2ºC' scenarios, compared with equivalent values presented in Bauer et al.[13] (top table) and McGlade & Ekins[55] (bottom table). The cumulative revenues from fossil fuels in the same period are compared with the scenarios presented in [[13]] (middle table). The comparison includes the scenarios presented in McGlade & Ekins[55] using the model TIAM-UCL, and the different models and values presented in Bauer et al.[13]. Note that to be consistent with these sources, revenue values are cumulated and discounted starting from 2011, and therefore are not directly comparable with those in Suppl. Table 2, which are discounted starting in 2017.

Cumulative production (our paper) and consumption of fossil fuels between 2011-2050 [ZJ]

		Oil		Natural Gas		Coal	
		min	max	min	max	min	max
This work	2°C	5.9		5.4		3.8	
	Tech. Diff. Trajectory	7.0		5.9		8.2	
	IEA Expectations	7.9		6.6		7.8	
Bauer et al. [[13]]	450-e values	6.4	8.8	3.8	7.8	2.4	7.7
	450-e models	IMAGE	DNE21	WITCH	REMIND	REMIND	GCAM
	550-e values	6.5	9.7	5.0	9.1	4.4	8.6
	550-e models	MERGE-ETL	MESSAGE	WITCH	REMIND	REMIND	IMACLIM
	NoPol Values	7.0	10.8	5.5	9.2	7.8	17.8
	NoPol models	MERGE-ETL	IMACLIM	IMACLIM	REMIND	MESSAGE	IMACLIM
McGlade & Ekins [[55]]	2degC Values	6.2	7.2	5.5	7.0	2.2	3.7
	2degC sub-scenario	OILLOW	DEMHIGH	FFCHIGH	DEMHIGH	NOCCS	FFCHIGH
	3degC	7.6		6.4		7.1	
	5degC	8.1		6.2		8.7	

Cumulative revenues from fossil fuels between 2011-2050 [US$ trillion NPV 2010 discounted at 5%]

		Oil		Natural Gas		Coal	
		min	max	min	max	min	max
This work	2°C	13.8		7.2		1.0	
	Tech. Diff. Trajectory	16.8		7.7		1.7	
	IEA Expectations	18.5		8.7		1.6	
Bauer et al. [[13]]	450-e values	14.2	68.9	8.8	41.0	2.1	9.3
	450-e models	MESSAGE	DNE21	GCAM	DNE21	REMIND	POLES
	550-e values	16.6	73.4	8.9	41.1	3.3	11.3
	550-e models	MESSAGE	DNE21	GCAM	DNE21	REMIND	DNE21
	NoPol Values	18.5	74.4	9.1	39.5	5.9	20.7
	NoPol models	MESSAGE	DNE21	GCAM	DNE21	GCAM	DNE21



Suppl. Figure 9 | Comparison of E3ME-FTT primary fossil-fuel demand to other IAMs, cumulated over the 2011-2050 period**.** Comparison of E3ME-FTT scenarios of this work to the AR5 ensemble of model results from 11 models, including TIAM-UCL used by McGlade & Ekins[55], showing model results for various model comparison projects and studies (indicated in each panel). The vertical lines are guides to the eye indicating the total fossil fuel demand from the scenarios of this work. Data obtained from the AR5 scenario database at tntcat.iiasa.ac.at/AR5DB/.

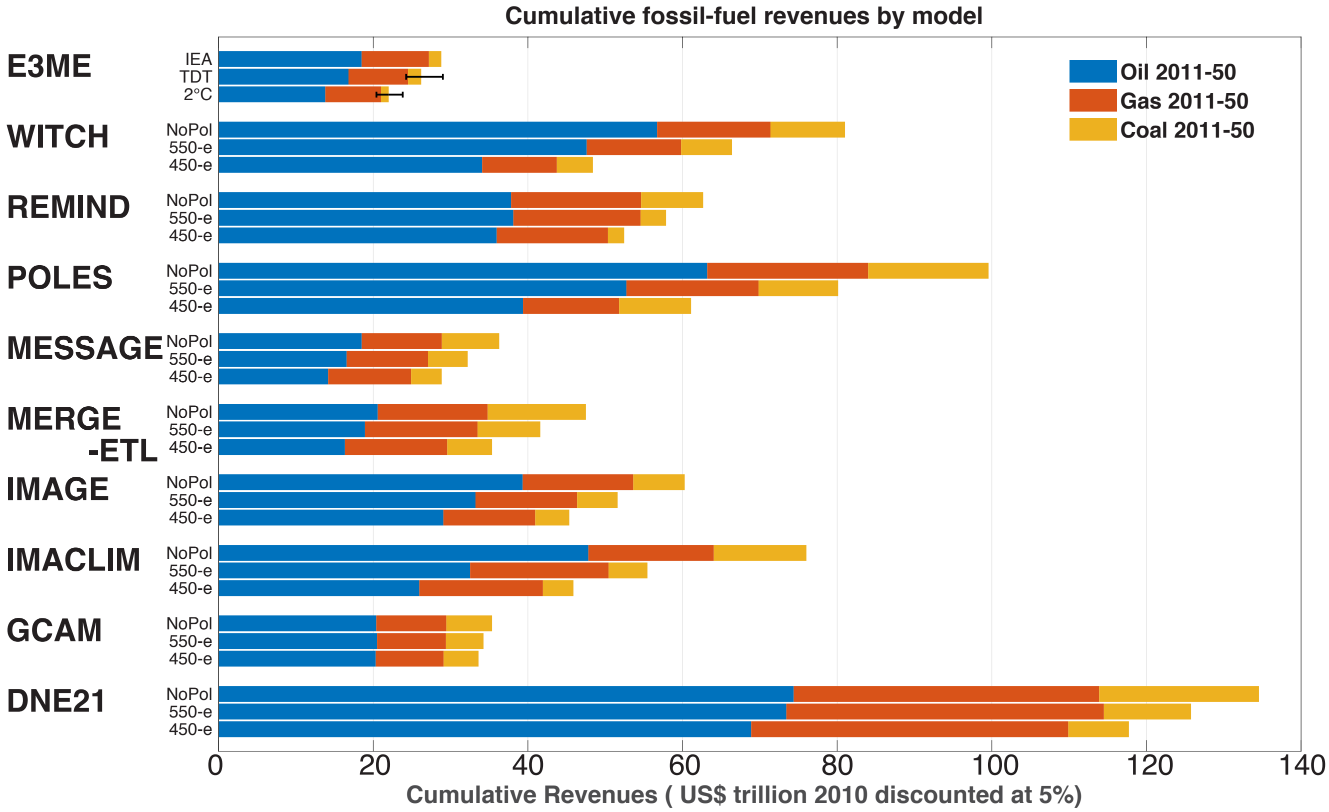
Suppl. Table 6 | Comparison of GENIE with other models. GENIE-1 global mean warming (2090-2005) compared to CMIP5[56] and EMIC AR5 inter-comparison[57]. AR5 and CMIP5 warming is 2081-2100 mean relative to the 1985-2005 baseline. Data are ensemble median (5%, 95% confidence) (GENIE-1) and ensemble mean (minimum, maximum) (EMIC AR5 and CMIP5).

	GENIE-1	EMIC AR5	CMIP5
RCP2.6	0.9 (0.6, 1.5)	1.0 (0.6, 1.4)	1.0 (0.0, 2.0)
RCP4.5	1.7 (1.2, 2.6)	1.7 (0.9, 2.4)	1.8 (1.0, 2.8)
RCP6.0	2.2 (1.7, 3.2)	2.1 (1.1, 2.8)	2.3 (1.5, 3.2)
RCP8.5	3.4 (2.7, 4.9)	3.1 (1.6, 4.1)	3.7 (2.5, 5.0)

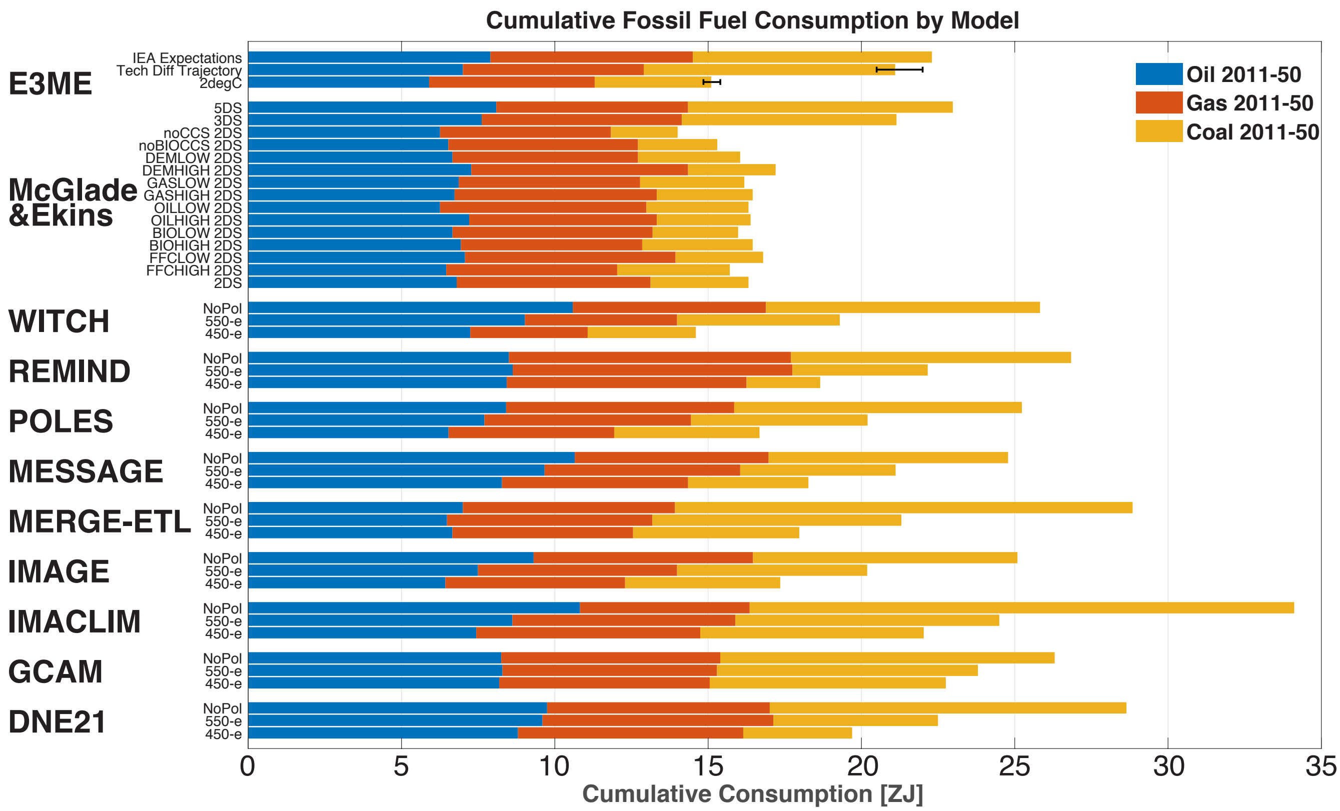
Suppl. Table 7 | Fossil fuel prices by scenario (2016$/bbl)

	Oil			**Coal**			**Gas**		
Scenario	**2016**	**2035**	**2050**	**2016**	**2035**	**2050**	**2016**	**2035**	**2050**
IEA	35.5	39.5	42.1	3.3	3.4	3.6	20.4	24.3	26.9
IEA SO	34.7	33.9	33.3	3.3	3.4	3.4	19.7	19.2	18.7
TDT	35.5	37.1	34.9	3.3	3.5	3.6	20.3	22.9	25.3
TDT SO	34.7	30.6	20.2	3.3	3.4	3.5	19.6	17.0	18.1
2°C	35.5	29.6	19.6	3.3	2.9	2.9	20.4	22.0	22.3
2°C SO	34.6	19.8	14.0	3.3	2.9	2.8	19.7	13.2	6.9
ν_0 test	35.0	24.1	16.4	3.3	2.9	2.8	20.0	18.9	15.5
TDT +	35.8	38.1	36.7	3.3	3.5	3.6	20.8	23.8	26.4
TDT -	35.4	36.4	34.0	3.3	3.4	3.6	19.8	22.1	24.4
2°C +	35.7	30.3	20.2	3.3	2.9	2.8	20.9	22.9	23.4
2°C -	35.4	29.4	19.0	3.3	3.0	2.9	19.9	20.6	20.4
2°C SO +	34.9	20.2	14.2	3.3	2.8	2.7	20.3	16.3	8.3
2°C SO -	34.5	19.8	13.9	3.3	2.9	2.8	19.2	9.7	5.9

Notes: 'ν_0 test' stands for the sensitivity test on the reserve to production ratio (Suppl. Fig. 6). '+' and '-' stand for the combined sensitivity tests given in Suppl. Tables 3-4, while 'SO' stands for sell-out scenarios. Prices are obtained by scaling 2016 marginal costs from this model to 2016 fossil fuel prices, and are used to determine SFFA losses.



Suppl. Figure 10 | Comparison of E3ME-FTT fossil-fuel revenues to other IAMs, cumulated over the 2011-2050 period**.** Comparison of E3ME-FTT scenarios of this work to those in Bauer et. al.[13] Data obtained from the author.



Suppl. Figure 11 | Comparison of E3ME-FTT primary fossil-fuel demand to other IAMs, cumulated over the 2011-2050 period. Comparison of E3ME-FTT scenarios of this work and that in Bauer et al.[13] and McGlade & Ekins[55] Data obtained from the author.

Suppl. Table 8 | Sectoral impacts of SFFAs in chosen regions and sectors

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
Global	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	0.7	0.6	1.2	0.4	0.5	0.5	0.7	0.4
Extraction sectors	-9.9	-10.0	-7.1	-6.9	-9.5	-9.7	-6.8	-6.5
Basic manufacturing	-0.6	0.9	0.8	1.1	-0.3	0.8	0.9	1.0
Advanced manufacturing	-0.2	1.7	1.3	1.2	-0.2	1.7	1.1	0.9
Utilities	-2.1	1.3	-3.2	-4.7	-2.1	1.3	-3.4	-4.8
Construction	0.3	0.9	2.8	2.4	0.3	1.0	2.7	2.2
Distribution and retail	-0.7	0.6	1.1	1.4	-0.7	0.7	0.9	1.0
Transport and communications	-0.3	1.1	2.0	1.6	-1.0	0.8	0.4	0.9
Business services	0.4	0.3	1.8	0.8	-0.2	0.2	0.9	0.6
Public services	-1.8	-1.2	-1.3	-0.9	-1.9	-1.3	-1.5	-1.1
All sectors	-0.5	0.4	0.9	0.7	-0.7	0.3	0.5	0.5

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
EU	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	2.7	0.1	8.5	-0.6	2.3	0.2	4.9	-0.3
Extraction sectors	-10.1	-6.0	-5.7	-3.0	-10.0	-5.5	-6.2	-3.4
Basic manufacturing	0.7	-0.2	1.7	-0.5	0.6	-0.1	1.2	-0.5
Advanced manufacturing	0.7	0.3	2.7	1.0	0.1	0.0	1.8	0.7
Utilities	0.7	0.1	1.1	0.1	0.6	0.2	0.8	0.2
Construction	1.2	0.2	2.8	0.5	0.8	0.1	2.3	0.4
Distribution and retail	-7.3	-6.9	-6.5	-6.2	-7.5	-6.9	-7.4	-6.5
Transport and communications	1.2	0.5	1.7	0.3	1.1	0.4	1.7	0.3
Business services	0.9	0.4	2.1	0.4	0.6	0.4	1.4	0.3
Public services	1.6	0.6	2.4	0.9	1.3	0.5	1.2	0.3
All sectors	0.8	0.4	1.9	0.7	0.6	0.3	1.2	0.5

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
US	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	-0.3	0.0	4.7	0.0	-3.3	0.0	-2.7	0.0
Extraction sectors	-50.6	-16.2	-45.2	-21.8	-49.1	-14.8	-42.3	-16.8
Basic manufacturing	-7.0	-0.5	-2.1	9.7	-6.6	-1.1	-1.6	9.3
Advanced manufacturing	-8.6	0.7	0.1	2.9	-11.5	0.7	-3.6	2.7
Utilities	-8.0	-7.2	-11.3	-9.5	-7.9	-6.8	-11.2	-8.8
Construction	-6.3	-8.3	-1.7	-0.9	-7.1	-9.3	-2.8	-2.1
Distribution and retail	-5.4	0.0	-0.3	0.8	-6.4	-0.4	-1.6	0.1
Transport and communications	-3.0	0.5	0.6	2.9	-4.8	0.0	-2.0	2.1
Business services	-1.6	-1.2	1.5	0.2	-3.5	-1.8	-1.5	-0.5
Public services	-3.5	-2.9	-2.3	-2.0	-3.6	-2.8	-2.3	-1.9
All sectors	-4.6	-1.7	-1.0	0.0	-5.7	-1.9	-2.5	-0.3

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
Canada	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	-8.5	1.2	0.9	-6.3	-9.3	1.5	-0.7	-5.8
Extraction sectors	-81.9	-74.0	-81.0	-76.6	-81.3	-73.1	-80.5	-75.9
Basic manufacturing	-8.1	-2.7	-6.4	-1.2	-8.0	-2.9	-6.0	-1.6
Advanced manufacturing	-4.8	-2.8	-3.4	-3.0	-4.6	-2.6	-3.2	-2.7
Utilities	-4.5	-4.5	-8.0	-8.1	-4.0	-4.3	-7.8	-8.0
Construction	-10.6	-7.8	-5.7	-5.3	-10.1	-7.4	-5.6	-5.2
Distribution and retail	-17.2	-9.6	-14.2	-8.3	-16.5	-9.2	-14.0	-8.2
Transport and communications	-13.6	-6.6	-13.1	0.3	-13.2	-6.4	-13.2	-0.4
Business services	-15.2	-5.6	-13.4	-6.9	-14.7	-5.4	-13.7	-6.8
Public services	-20.3	-20.3	-19.3	-19.2	-19.6	-19.6	-18.9	-18.9
All sectors	-16.1	-9.4	-13.6	-8.3	-15.6	-9.1	-13.4	-8.2

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
China	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	2.0	0.1	4.5	0.2	2.0	0.1	3.6	0.2
Extraction sectors	-21.4	-33.6	-10.5	-19.6	-21.1	-33.1	-10.0	-18.9
Basic manufacturing	0.5	0.7	2.0	0.5	0.7	0.8	1.4	0.4
Advanced manufacturing	0.1	-0.2	1.4	0.8	0.8	0.1	1.4	0.6
Utilities	0.8	0.6	1.2	0.9	1.2	0.9	1.2	0.9
Construction	0.8	0.7	3.7	1.2	1.2	0.8	3.9	0.6
Distribution and retail	1.6	2.7	5.6	5.1	2.3	3.3	5.5	4.7
Transport and communications	1.4	1.3	5.7	3.2	1.6	1.4	4.7	2.8
Business services	1.1	0.1	2.6	0.2	1.6	0.1	2.5	0.1
Public services	0.2	0.2	0.4	0.3	0.2	0.2	0.4	0.3
All sectors	0.3	0.3	2.2	1.0	0.6	0.4	1.9	0.9

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
India	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	0.9	0.4	0.5	-0.8	0.8	0.2	0.0	-0.7
Extraction sectors	-18.2	-11.4	12.7	-22.9	-15.8	-11.1	11.8	-22.6
Basic manufacturing	-10.5	1.0	-11.6	0.6	-4.5	1.1	-1.0	0.7
Advanced manufacturing	-4.0	3.1	3.9	2.1	-1.9	3.2	4.5	1.6
Utilities	-4.2	-4.1	26.7	25.2	-4.4	-4.2	26.1	24.7
Construction	1.3	1.8	3.9	3.1	1.5	2.1	3.8	2.9
Distribution and retail	0.4	-0.4	15.1	3.5	0.5	-0.5	5.5	1.1
Transport and communications	4.0	3.3	5.7	3.1	2.4	2.3	1.3	0.7
Business services	0.6	0.1	3.4	0.5	0.4	0.2	1.8	0.4
Public services	0.2	0.2	0.7	0.7	0.1	0.1	0.2	0.3
All sectors	-1.1	0.6	2.1	1.0	-0.2	0.5	2.1	0.5

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
Russia	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	-0.5	1.4	-1.2	1.1	-0.4	1.2	-1.4	0.2
Extraction sectors	-18.4	-37.2	-24.2	-45.0	-18.1	-37.0	-24.0	-45.0
Basic manufacturing	-1.0	0.0	-1.7	-0.6	-1.0	0.0	-1.6	-0.9
Advanced manufacturing	-1.2	0.8	-1.1	0.2	-0.8	0.7	-0.3	0.4
Utilities	-10.4	-10.9	-13.5	-14.4	-10.3	-10.8	-13.6	-14.5
Construction	0.1	-0.3	0.7	1.3	0.5	0.1	1.1	1.0
Distribution and retail	-1.2	0.1	-1.2	-0.4	-0.9	0.1	-1.0	-0.3
Transport and communications	-0.2	-0.2	-0.6	-0.1	-0.1	-0.2	-0.5	-0.1
Business services	0.6	-0.3	1.4	0.6	0.8	-0.3	1.5	0.5
Public services	-5.9	-4.6	-10.1	-8.3	-5.8	-4.5	-10.1	-8.3
All sectors	-2.3	-1.3	-2.8	-2.2	-2.1	-1.3	-2.6	-2.3

	IEA expectations to 2ºC sellout				Tech. Diff. Trajectory to 2ºC sellout			
OPEC	2035		2050		2035		2050	
% change in	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.	Prod.	Empl.
Agriculture	-0.6	-0.2	-0.9	-0.1	-1.2	-0.2	-1.7	-0.1
Extraction sectors	7.8	3.2	2.4	0.9	7.9	3.3	2.5	0.9
Basic manufacturing	-2.2	0.4	-3.3	0.8	-1.7	0.1	-1.8	0.2
Advanced manufacturing	0.0	0.1	0.1	0.2	-0.9	-0.1	-0.8	-0.1
Utilities	-3.7	-11.7	-4.1	-16.7	-4.0	-12.4	-4.3	-17.3
Construction	-1.5	-0.7	0.3	0.1	-1.8	-0.8	-0.2	0.0
Distribution and retail	-2.3	-0.5	-4.6	-0.9	-1.3	-0.1	-3.6	-0.4
Transport and communications	0.6	0.4	0.5	0.6	0.0	0.4	-0.7	0.5
Business services	0.1	0.2	-0.1	-0.2	-0.5	0.2	-1.0	-0.4
Public services	-15.6	-17.5	-13.1	-10.8	-15.8	-17.7	-13.6	-11.3
All sectors	-1.7	-2.5	-2.3	-1.6	-1.9	-2.5	-2.7	-1.7

References

1 Clarke, L. *et al.* Chapter 6: Assessing transformation pathways, in Climate Change 2017, Working Group III, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (2014).

2 Edenhofer, O. *et al.* The economics of low stabilization: model comparison of mitigation strategies and costs. *The Energy Journal*, 11-48 (2010).

3 Mercure, J. *et al.* Policy-induced energy technological innovation and finance for low-carbon economic growth. Study on the macroeconomics of energy and climate policies., (2016). https://ec.europa.eu/energy/sites/ener/files/documents/ENER Macro-Energy_Innovation_D2 Final %28Ares registered%29.pdf

4 Pollitt, H. & Mercure, J.-F. The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. *Climate Policy*, 1-14 (2017).

5 Dafermos, Y., Nikolaidi, M. & Galanis, G. A stock-flow-fund ecological macroeconomic model. *Ecological Economics* **131**, 191-207 (2017).

6 Giraud, G., Mc Isaac, F., Bovari, E. & Zatsepina, E. Coping with the Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. (2016).

7 McLeay, M., Radia, A. & Thomas, R. Money in the modern economy: an introduction. (2014). http://www.bankofengland.co.uk/publications/Pages/quarterlybulletin/2014/qb14q1.aspx

8 McLeay, M., Radia, A. & Thomas, R. Money creation in the modern economy. (2014). http://www.bankofengland.co.uk/publications/Pages/quarterlybulletin/2014/qb14q1.aspx

9 Lavoie, M. *Post-Keynesian economics: new foundations*. (Edward Elgar Publishing, 2014).

10 Grubb, M., Carraro, C. & Schellnhuber, J. Endogenous Technological Change and the Economics of Atmospheric Stabilisation. *The Energy Journal* **27** (2006).

11 Kriegler, E. *et al.* Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change* **90**, 24-44 (2015).

12 Kriegler, E. *et al.* The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* **123**, 353-367 (2014).

13 Bauer, N. *et al.* CO 2 emission mitigation and fossil fuel markets: dynamic and international aspects of climate policies. *Technological Forecasting and Social Change* **90**, 243-256 (2015).

14 IEA. World Energy Model Documentation 2017 Version. (IEA, 2017). https://www.iea.org/media/weowebsite/2017/WEM_Documentation_WEO2017.pdf

15 Köhler, J., Grubb, M., Popp, D. & Edenhofer, O. The transition to endogenous technical change in climate-economy models: a technical overview to the innovation modeling comparison project. *The Energy Journal*, 17-55 (2006).

16 IEA/OECD. Projected Costs of Generating Electricity. *IEA/OECD* (2010).

17 IEA/OECD. Projected Costs of Generating Electricity. *IEA/OECD* (2015).

18 Busse, M. R., Knittel, C. R. & Zettelmeyer, F. Are consumers myopic? Evidence from new and used car purchases. *American Economic Review* **103**, 220-256 (2013).

19 OECD. Stimulating Low-Carbon Vehicle Technologies. (OECD, 2011).

20 Geels, F. W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy* **31**, 1257-1274 (2002).

21 Holtz, G. *et al.* Prospects of modelling societal transitions: Position paper of an emerging community. *Environmental Innovation and Societal Transitions* **17**, 41-58 (2015).

22 Geels, F. W. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technology analysis & strategic management* **17**, 445-476 (2005).

23 Grübler, A., Nakićenović, N. & Victor, D. G. Dynamics of energy technologies and global change. *Energy policy* **27**, 247-280 (1999).
24 Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy* **50**, 81-94 (2012).
25 Mercure, J.-F. & Salas, P. On the global economic potentials and marginal costs of non-renewable resources and the price of energy commodities. *Energy Policy* **63**, 469-483 (2013).
26 Sinn, H.-W. Public policies against global warming: a supply side approach. *International Tax and Public Finance* **15**, 360-394 (2008).
27 Blanchard, O. J. The crisis: basic mechanisms, and appropriate policies. (IMF Working Paper, 2008). https://www.imf.org/external/pubs/ft/wp/2009/wp0980.pdf
28 Battiston, S., Mandel, A., Monasterolo, I., Schütze, F. & Visentin, G. A climate stress-test of the financial system. *Nat Clim Change* **7**, 283-288 (2017).
29 TCFD. Recommendations of the Task Force on Climate-related Financial Disclosures. (Task Force on Climate-Related Financial Disclosures, 2017). https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Report-062817.pdf
30 IEA. *World Energy Outlook*. (OECD/IEA, 2016).
31 Dietz, S., Bowen, A., Dixon, C. & Gradwell, P. /Climate value at risk/'of global financial assets. *Nat Clim Change* **6**, 676-679 (2016).
32 Nordhaus, W. D. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 201609244 (2017).
33 Lee, S., Pollitt, H. & Park, S.-J. *Low-carbon, Sustainable Future in East Asia: Improving Energy Systems, Taxation and Policy Cooperation*. (Routledge, 2015).
34 Armington, P. S. A theory of demand for products distinguished by place of production. *Staff Papers* **16**, 159-178 (1969).
35 Mercure, J.-F. & Salas, P. An assessement of global energy resource economic potentials. *Energy* **46**, 322-336 (2012).
36 Mercure, J.-F. FTT: Power: A global model of the power sector with induced technological change and natural resource depletion. *Energy Policy* **48**, 799-811 (2012).
37 Knobloch, F., Pollitt, H., Chewpreecha, U. & Mercure, J.-F. Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5C. *ArXiv preprint* (2017).
38 Mercure, J.-F. An age structured demographic theory of technological change. *Journal of Evolutionary Economics* **25**, 787-820 (2015).
39 Mercure, J.-F., Lam, A., Billington, S. & Pollitt, H. Integrated assessment modelling as a positive science: modelling policy impacts in road transport to meet a climate target well below 2C. *arXiv:1702.04133* (2017).
40 Mercure, J.-F. *et al.* The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. *Energy Policy* **73**, 686-700 (2014).
41 Mercure, J.-F. & Lam, A. The effectiveness of policy on consumer choices for private road passenger transport emissions reductions in six major economies. *Environ Res Lett* **10**, 064008 (2015).
42 Knobloch, F., Mercure, J.-F., Pollitt, H., Chewpreecha, U. & Lewney, R. A technical analysis of FTT:Heat – A simulation model for technological change in the residential heating sector. (European Commission, DG Energy, 2017). https://ec.europa.eu/energy/sites/ener/files/documents/technical_analysis_residential_heat.pdf
43 Cambridge Econometrics. The E3ME Model. (2017). http://www.e3me.com
44 Barker, T., Alexandri, E., Mercure, J.-F., Ogawa, Y. & Pollitt, H. GDP and employment effects of policies to close the 2020 emissions gap. *Climate Policy* **16**, 393-414 (2016).
45 Cambridge Econometrics. Employment Effects of selected scenarios from the Energy roadmap 2050. (2013). http://ec.europa.eu/energy/sites/ener/files/documents/2013_report_employment_effects_roadmap_2050_2.pdf

46 Cambridge Econometrics. Assessing the Employment and Social Impact of Energy Efficiency. (November, 2015). http://ec.europa.eu/energy/sites/ener/files/documents/CE_EE_Jobs_main 18Nov2015.pdf
47 Mercure, J.-F., Pollitt, H., Edwards, N. R., Holden, P. B. & Vinuales, J. E. Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews* **20**, 195-208, doi:https://doi.org/10.1016/j.esr.2018.03.003 (2018).
48 Pollitt, H., Alexandri, E., Chewpreecha, U. & Klaassen, G. Macroeconomic analysis of the employment impacts of future EU climate policies. *Climate Policy* **15**, 604-625 (2015).
49 Edwards, N. R. & Marsh, R. Uncertainties due to transport-parameter sensitivity in an efficient 3-D ocean-climate model. *Climate Dynamics* **24**, 415-433 (2005).
50 Ridgwell, A. & Hargreaves, J. Regulation of atmospheric CO2 by deep‐sea sediments in an Earth system model. *Global Biogeochem Cy* **21** (2007).
51 Holden, P. B., Edwards, N. R., Gerten, D. & Schaphoff, S. A model-based constraint on CO 2 fertilisation. *Biogeosciences* **10**, 339-355 (2013).
52 Williamson, M., Lenton, T., Shepherd, J. & Edwards, N. An efficient numerical terrestrial scheme (ENTS) for Earth system modelling. *Ecological Modelling* **198**, 362-374 (2006).
53 Ridgwell, A. *et al.* Marine geochemical data assimilation in an efficient Earth System Model of global biogeochemical cycling. *Biogeosciences* **4**, 87-104 (2007).
54 Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 C. *Nature* **458**, 1158 (2009).
55 McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg] C. *Nature* **517**, 187-190 (2015).
56 Knutti, R. & Sedláček, J. Robustness and uncertainties in the new CMIP5 climate model projections. *Nat Clim Change* **3**, 369-373 (2013).
57 Zickfeld, K. *et al.* Long-term climate change commitment and reversibility: an EMIC intercomparison. *J Climate* **26**, 5782-5809 (2013).